DEVELOPMENT OF RAPID PROTOTYPING AND TOOLING FOR COMPOSITE AND SHEET METAL APPLICATIONS

by

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DECEMBER 1998

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A Thesis Submitted in
Partial Fulfillment of the Requirements
for the degree of

MASTER OF TECHNOLOGY

by

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CERTIFICATE

This is to certify that the work contained in the thesis entitled, **"Development of Rapid Prototyping and Tooling for Composite and Sheet Metal Application "** by *Rahul Kumar* has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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IIT Kanpur,

December, 1998

ACKNOWLEDGEMENTS

I would like to express my deep sense of gratitude to my ever-cherished guide Dr. B. Sahay for his invaluable guidance and help throughout my M. Tech. programme. I am sincerely thankful for his valuable suggestion in my academic as well as personal life. He has been and would be a constant source of encouragement to me throughout my life, particularly for his kind and forever-calm nature even in the tough situation

I am paying great regards to Dr. Sanjay G. Dhande for giving me an opportunity to work in leading areas of the world like CAD, RP & RT. He was and continues to be a model of dedication, discipline, and hard work, which was a great inspiration to me. It would not be an exaggeration to say that my experiences with him tempt me to pursue my remaining career with him.

I am grateful to Dr. Prashant Kumar for the useful discussion I had with him regarding my thesis work. My sincere thanks and regards to Shri A. D. Bhatt, research scholar for the technical discussion I had with him, his motivations and advice. Thanks to Shri Sanat Agrawal and Shri Puneet Tandon, research scholars for suggestion and support.

I am thankful to my CAD-P friends M. Anil Kumar, Manoj Kr. Sinha, Vikas Bansal, V. Sridharan, B. Rajkumar (Scientist), Siddharth, Asit Agrawal, K. R. Arvind, Sandeep, L.Srinivas, and Chandrashekhar, Swapnil, K. Siva Prasad, Ashish Kulkarni. My sincere thanks to Sridharan for his throughout assistance, amity and company.

Goods friends make the life enjoyable. I wish to thank to all my friends in I. I. T. K. campus, who shared and stood by me during days of happiness as well as difficulties, I am thankful.

I would like to thank to all CAD–P Lab and Stress Analysis Lab staffs, Shri C. P. Singh, Shri S. C. Gupta, Shri Rajesh Srivastava, Shri Rabindra Srivastava, Shri BabuLal, Shri Sarju Prasad, Shri Anurag Goel, Shri Pandey and many others for their helps in one way or others.

I wish to express my heartfelt thanks to my parents, uncles, bua, and elder brother, for their endless love, encouragement and endurance during my stay at I. I. T. Kanpur.

Finally, I am grateful to the Almighty for what I am today.

Rahul Kumar

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Dedicated

To

My Parents

ABSTRACT

In the present, work new methods of making a tool for sheet metal forming processes and FRP composite processing have been developed. These methods are very fast methods. This approach has been developed using the new technology of Rapid Prototyping process and MCP Alloy System. In contrast to the common process for making the tool i.e. a machining process, here tool is made via casting process using a special alloy – MCP 137.

In this work, pattern for a making tool has been made on different RP processes like Fused Deposition Modelling (FDM) and Solid Ground Curing (SGC). Also comparative study has been done for both these two processes for the feasibility of making the tool. In FDM process the pattern is made by depositing a thermoplastic material such as ABS 400 layer by layer. In SGC process, acrylic-based photopolymers are used to make the model by curing the liquid resin by ultraviolet (UV) light. Different methods for making the tool using the RP patterns and a special low melting alloy (MCP –137) have been tried out to get a good tool. It is found that the press tool made out of this process is suitable for FRP composite processing and sheet metal forming. Two types of FRP i.e. FRP cloth composites and FRP unidirectional prepreg have been processed on this tool and the results were studied. The evaluation of the press tool was also carried out using computational approach for different applications. The tools were analyzed using I-DEAS FEA software. It has been found that the die is suitable for different composite processing and it is also suitable for sheet metal process up to some extent.

Chapter 1

INTRODUCTION

1.1 Background Information

A large number of technologies have emerged during the past few years in response to the pressing need for reducing product development lead times. There are two bottlenecks in the product development process as practiced today. The first one has to do with getting the design right and the second one has to do with obtaining the physical prototype given a computer model or a drawing of the part. In most product development cycles, the design is frozen only after incorporating feedback based on the physical prototype thereby coupling the two problems.

The first bottleneck is due to the sequential nature of the design tasks and the lack of automation in transition between tasks in product development. This has resulted in the concept of virtual prototyping or digital prototyping. The objective here is to use software tools to design both the part and the means to realize the part. By enabling CAD systems to support downstream life-cycle concerns during the design stage, it is possible to perform the design–analyze-evaluate-modify iterations in the computer using the digital prototype to realize the final design in a timely and cost effective manner.

The virtual (or digital) prototype offers much greater flexibility in terms of the ability to vary design parameters and the environment in which the part will function. A physical prototype, however, becomes essential for:

(1) Communicating the design to tooling designers,

(2) To begin planning for manufacturing and design jigs and fixtures for the manufacture and assembly of the product,

(3) To initiate vendor development by purchase section, and

(4) Communicating the design to personnel in marketing and other decision-maker in organization.

This is because the representation of design thus far in the cycle - either a computer model or engineering drawings/blueprints is incomprehensible to a large number of the people involved in product development tasks.

Rapid prototyping processes are able to eliminate this problem by obtaining the physical prototype.

Rapid prototyping has become possible, due to the development of a new manufacturing paradigm, where unlike the earlier forming or material removal processes, shape is realized by adding material. This addition could be through deposition or by a phase transformation.

Rapid prototyping refers to a class of processes that enable physical realization of a shape without the use of any tooling or material removal. Directly driven by a CAD model, these processes build the part layer by layer either depositing the material (e.g. Fused Deposition Modeling) or by changing the phase of the material (e.g. Solid Ground Curing). This technology is variously referred to as Layered Manufacturing, Solid Freeform Fabrication, 3D Printing. There are several technologies in different stages of maturation that are available.

Almost all rapid prototyping technologies currently in use are restrictive in size of prototype possible and do not yield prototypes in material of end-use and in the numbers required for prototype testing and evaluation. It is desirable to have a method, which will allow us to produce small quantities of functional prototype in their end use material. Most of the existing rapid prototyping systems cannot provide the product characteristics associated with the end use material. The fabrication of conventional hard tooling requires a large investment and considerable fabrication time, which can only be economically justified if there are no further changes in design and through long production runs of thousands of parts. Rapid Tooling or Soft Tooling is the solution for this problem, which makes the functional parts in material of end use in small quantity in very short time and less than10% cost of the conventional process.

1.2 Soft Metal Tooling – An Introduction

Although it is possible to make 'prototype' very quickly by the various Rapid Prototyping & Manufacturing techniques, designing often requires a prototype made in

the end use material by the process used in final production, so, that, there can be confidence in the design and the end material as well as the economics of production. But the models from the existing RP & M techniques are made from a limited variety of materials such as ABS plastic, Paper, Resin etc. that usually have poor to marginal mechanical and thermal properties compared to end use material. With the outbreak of new computer based and polymer based technologies, it is now possible to make a physical prototype by a process used in final production in the end use material from soft tooling.

Soft tooling can be defined in various ways. The most obvious definition corresponds to the type of material used for manufacturing the tool. Hard tooling. therefore, is referred to that made from hardened tool steels. Materials with lower hardness are considered "Soft" e.g. silicones, low melting alloy, rubbers etc. So, tools. which are made from these soft materials, are called soft tool.

It is also possible to define soft tooling by the method of manufacture, most hardened steel tools being manufactured by either conventional machine cutting processes of variations of Electrical Discharge Machining (EDM) and maximum of soft tools are made by a simple process like casting.

Another definition is that tooling is being associated with low cost and so the term soft.

Finally, soft tools can also be defined as those, which are required for small production quantities.

Soft Tooling Techniques:

Many techniques are available for producing soft tool, the key among them are

(1) Press Tool die using MCP low melting alloy.

(2) Silicone Rubber Molding

(3) Epoxy Tooling

(4) Spray Metal Tooling

(5) Direct Metal Laser Sintering

(6) Keltool

(7) Laminated Laser Cut Cavities

1.3 Present Work -Goals and Objectives

In the present work an attempt has been made to make the press- tool die for sheet metal forming processes and for processing of FRP composites using MCP-Low Melting Alloy and RP pattern. RP patterns have been made on different type of RP processes those are available at CAD-P Lab I. I. T. Kanpur. The main goal is to establish the process itself. One of the objectives is to prove the capabilities of RP and RT to the Indian Industries. Different types of processes are developed to make the press tool die using RP-part as pattern. These processes are to be evaluated both qualitatively as well quantitatively. Quantitative evaluation has been done for strength analysis of the dies. For strength analysis, FEM has been used as the approach of evaluation.

1.4 Thesis Layout

In Chapter 1 general introduction about the topic is discussed. The procedure for creating Computer-aided solid model of a prototype using parametric solid modeling tool and processing of the CAD-model is discussed in Chapter 2. Different types of RP processes i.e. Fused Deposition Modeling (FDM) and Solid Ground Curing (SGC) are discussed in Chapter 2 because for making Press-tool dies, patterns which have been made by these processes, are used.

In Chapter 3, different types of processes are described for making the die using the RP patterns and also a procedure for making the part out of FRP composites, using the die, is described in detail.

The strength analysis of dies has been done for two simple parts using FEM as a tool, which is discussed in detail in Chapter 4.

Finally, the thesis ends with the conclusion and suggestions for future work in Chapter 5.

Chapter 2

RAPID PROTOTYPING

2.1 Introduction

In a competitive, increasingly global economic environment where high quality and fast time-to market are critical to a products success, engineering designers to artists were looking for a tool which can convert their thought and ideas regarding a product to a physical object. One promising set of emerging technologies is rapid prototyping, which allows physical part to be produced quickly from three-dimensional CAD data. Advancement in computer graphics added a new era in this field.

With rapid prototyping systems, engineers can build conceptual models and convey ideas more quickly and completely than with earlier methods. These systems can be used to build "quick-look" prototype for analyzing a part's form, fit and function. It can also be used as master pattern for developing rapid tool. Rapid prototyping can result in improved design quality, shorter design life cycles and lower development cost.

In RP processes, first a three-dimensional surface or solid geometry is created by means of a CAD system, called as virtual prototype. Then this CAD database is transferred to a rapid prototyping system, which convert these CAD data into a physical prototype. In all these RP process the final object is obtained by either gradual addition of material or by gradual binding or solidification or polymerization of material according to the requirements of the process. Traditional manufacturing technologies uses subtractive methods in the fabrication process. In contrast, rapid prototyping is characterized by using additive methods. Small fabrication primitives, such as drops or layers are applied over until the part is completed.

In this work, use was made of FDM1650 (Fused Deposition Modeling) machine of Stratasys Inc., and SOLIDER 4600(Solid Ground Curing Technology) of Cubital Inc. available in the CAD-Project laboratory, IIT Kanpur. In FDM machine, the material comes wound on a spool in the form of a filament approximately 1.8 mm in diameter, so it is both easy to load and easy to store. The material changeover for Stratasys system is relatively quick and simple, with little material waste . The details of these two processes are discussed below in detail.

2.2 Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) is the name of the technology used by commercial RP system from Stratasys, Inc. (Minneapolis, MN). The Stratasys systems are primarily targeted for the engineering office environment for use during the conceptual design stage of product development. Simple operation, inert materials and lack of fumes make the FDM process quite compatible with an office environment. In this process, a model is built using a thin filament of thermoplastic polymer namely ABS (Acrylonitrile Butadiene Styrene). The filament is heated and passed through a nozzle. The movement of the nozzle forms a layer, which is allowed to be solidified in the closed cabinet at 70°C, which takes a few seconds. For overhanging features, a separate nozzle head deposits the support material. Once the model is built, the support material can be easily broken off from the part. This process is inherently slow during layer deposition. However, no post curing is required in this process. Compared to other processes, FDM has relatively lower initial cost and easy operation. The running cost is also low. The surface in this case may need some finishing operations.

The basic input for any rapid prototyping process is an STL (STerioLithography) file that is obtained from a CAD model. The geometric modeling of the objects in computer aided design can be done using three methods viz., wireframe modeling, solid modeling and surface modeling. The wireframe modeling approach is not appropriate for STL creation, as it does not have the volumetric data. Solid modeling is very useful in the creation of volumetric object and hence helpful for STL creation. The solid modeling package, I-DEAS is used in the present work.I-DEAS is based on the variational technology that means that one can do any

operations on the model without specifying the dimensions in the initial stages. This variational technology could prove helpful in conceptual design wherein one can proceed with the ideas in his mind without any dimensions. At any stage the model can be edited for adding the dimensions and all the operations done on the model will be updated immediately.

2.2.1 STL File Format

Representation methods used to describe CAD geometry vary from one system to another. A standard interface is needed to convey geometric descriptions from various CAD packages to RP systems. The STL (STerioLithography) file format is the solution for this standard interface, which is used as a input in almost all RP system. In this format, the part is described by facets, which define the surface of the object. A facet consists of three vertex coordinates which define a triangle and the unit vector normal to the surface of the triangle. Normal defines which side of the surface of the part is enclosed. It has several distinct advantages like, it provides a simple method of representing 3-dimensional CAD data, it is a de facto standard and has been used by most of the RP processes and, the last thing is that it can provide simple files for data transfer for geometric shapes. One of the drawbacks of the STL file standard is that files tend to be quite voluminous. A new standard called a SOLI file has been developed by Cubital Inc., which reduces the computer memory.

The accuracy of the part depends on the triangulation of the STL file. Insufficient triangulation happens when not enough triangles are used to approximate the curved surfaces and surface types that have curvature in two directions like sphere and bicubic surface patches.

With increase in the number of triangles the error decreases. The number of triangles to be taken is at the discretion of the user and is controlled by parameters in the solid modeling packages. The biggest difficulty in generating the STL files is in the Vertex-to-Vertex rule, which states that:

Each edge in an STL file must exist between two and only two triangles.

2.2.2 FDM Hardware

The FDM1650 is a bench-top unit and can be placed next to a CAD workstation (Fig 2.1), as it requires no exhaust dust or other special accessories. The FDM head (Fig. 2.2) has two nozzles of hole diameters 0.305 and 0.635 mm are available, which can be changed as per the requiremen... The liquefire in the head melts the material at the temperature of 270° C for model material and 265°C for support material. The model is built in a closed cabinet maintained at 70°C.

Fig. 2.1: The FDM 1650 Machine

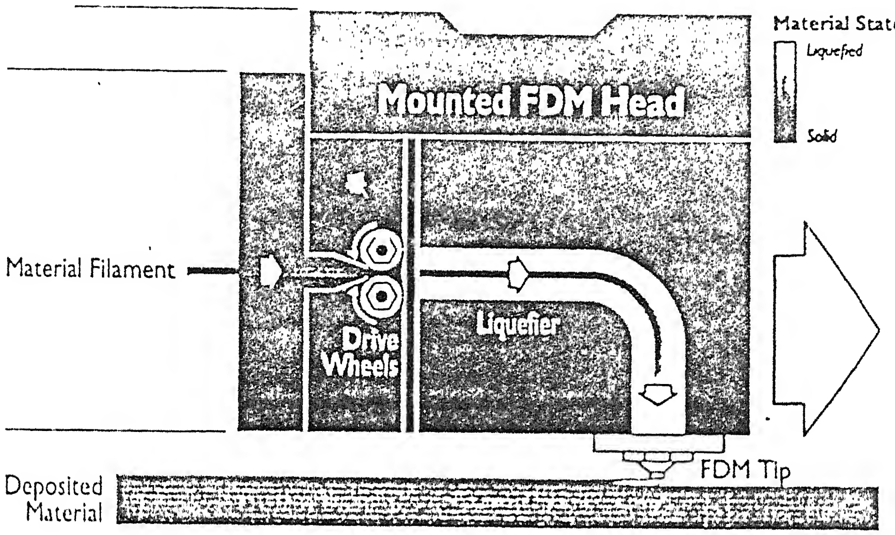


Fig. 2.2 Head of FDM1650

The head is mounted on a carriage which moves in x and y direction. The z movement is given to Z-stage platen. The model rests on the foam foundation provided on Z-stage platen. Both the model and support materials come in a wire form, from two different material spools located at the rear of the machine. On the front panel all the control buttons are provided to set the machine as per requirement. The controls such as x, y, z movement, temperature control, loading and unloading of material, etc. are available.

To run the FDM machine, first the nozzle tip of the required diameter is fitted on the head and the machine is cleaned. After sending the SML (Stratasys Machine Language) file, the initial x, y, z position of modeler tip is set properly with respect to foundation foam and the FDM machine is allowed to run. The head movement and material flow information for each slice curve is downloaded to the FDM1650. The FDM head deposits a perimeter road, which follows the shape of a slice curve, as shown in Fig.2.3. After the perimeter road, the head follows fill roads, which fill the solid areas inside the part. When a layer is deposited completely, the platform is lowered by the amount of slice thickness and the process is repeated.

The FDM1650 features the Break Away Support System (BASS), allowing the designer to create models with greater speed and precision. BASS uses a second nozzle to extrude the support material. The supports are designed to prop-up the

overhanging portions of the part during modeling. The head automatically extrudes the support tip out wherever required. The supports detached easily, making the finished product look better with minimum post-modeling finishing.

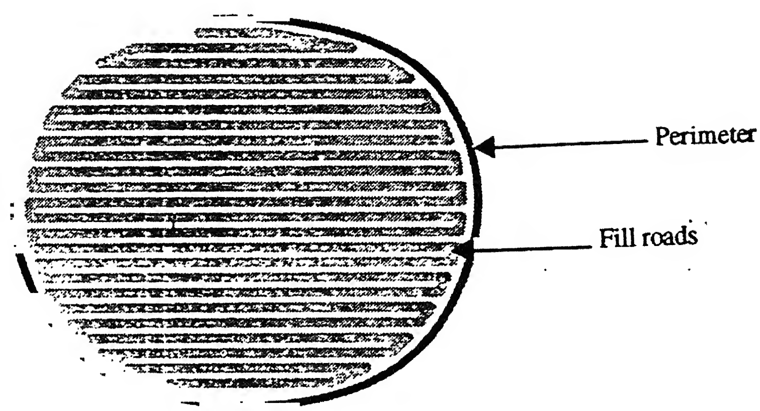


Fig. 2.3: Perimeter and Fill pattern for each layer

2.2.3 Model Material

The FDM1650 is capable of using inert, nontoxic material such as Investment Casting Wax and P400 Plastic (ABS Plastic). In the present work, P400 plastic is used for model making, as it is a tough plastic, which produces sturdy prototypes. P400 plastic is an Acrylonitrile Butadiene Styrene (ABS) based material having the properties given in Table-2.1.

Tensile Strength	34.5 MPa
Flexural Strength	65.5 MPa
Tensile Modulus	2482.8 MPa
Flexural Modulus	2620.7 MPa
Melting Point	270°C
Softening Point	104.4°C
Specific Gravity	1.05 gm/cc

Table-2.1: Properties of P400 – ABS Plastic

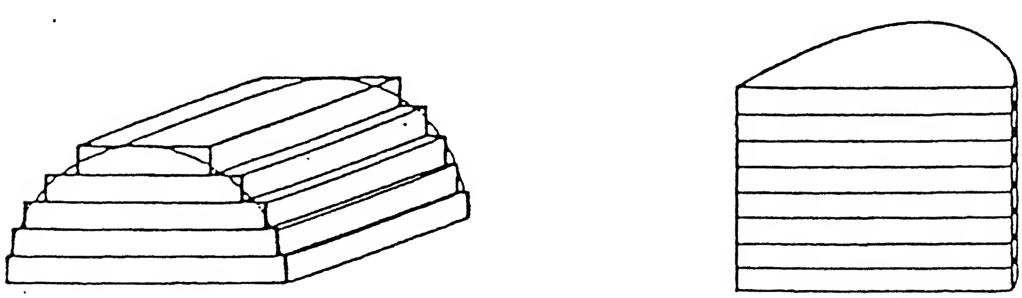
The material comes wound on a spool in the form of a filament approximately 1.8 mm in diameter, so it is both easy to load and easy to store. The material changeover for Stratasys system is relatively quick and simple, with little material wastage.

2.3 Process Parameters

The process parameters such as part orientation slice thickness and attributes of slice curve influence the surface finish, accuracy and the time taken by FDM to complete the prototype. These are separately discussed below.

2.3.1 Part Orientation

The designer's choice of part orientation has an impact on build time, part resolution, surface finish, support structures distortion, roundness, flatness, part tolerance, material cost, etc. All these attributes contribute to various degrees to the quality of the final product and have to be considered to have preferred orientation, which will require minimum running time, minimum support structure and good surface finish. Minimizing the height of the geometry in z-axis will reduce the number of layers required, thereby decreasing the build time; but it may give rough surfaces, e.g. a long cylinder. For good surface finish, the part orientation should be selected which will reduce the stairstep effect (Fig.2.4 (a)). Fig.2.4 (b) show how stairstep effect can be avoided by a proper choice of orientation.



(a) **(b)**

Fig. 2.4: Effect of part orientation on surface finish

2.3.2 Layer (Slice) Thickness

The thickness of each slice of the part affects the surface texture and the accuracy in the z-axis. Layer thickness is one of the most widely used variables in rapid prototyping. As dimensions in the slice axis are rounded-off in increments of the layer thickness, one should carefully assess the selection of layer thickness. FDM 1650 gives slice thickness of 0.178, 0.254 and 0.356 mm. More the slice thickness, lesser will be the running time, but that will also degrade the surface finish. In the present work, models with slice thickness of 0.254 are used. For this slice thickness, the nozzle tip of 0.305 mm is used.

2.3.3 Attributes of Slice Curve

When the FDM hardware builds a physical model, it lays down tracks of plastic called "roads". These roads follow the shape of slice curves. The selection of attributes such as road width, road height (slice thickness) and fill patterns (Fig.2.3) is dependent on the part accuracy and part building time. The part will be more accurate, if the road width and the road height is minimum, but then it will take more time to build the model. Increasing the road width increases the pores in the model. The default value for road width of 0.508 mm is used for making the prototypes.

2.4 Solid Ground Curing

This system is a liquid rapid prototyping (Fig. 2.5) system by Cubital Inc., Israel. It uses a liquid photosensitive (Ultra Violet Curable) resin to make the component and solid ground curing technology to make the prototype. The process is based on instant, simultaneous curing of whole cross sectional layer area as a result of which its speed is about eight times faster than other rapid prototyping systems. The SGC technology allows the models to be nested freely and placed in any orientation. The surface finish obtained in this process is much better than other processes. Porosity is very less in these models as each layer is made in a single shot and the whole layer is a solid unlike the SLA and FDM processes. As the models have less porosity these are more amenable for making tool for sheetmetál and composite processing. The total process is divided into two stages (Fig. 2.6).

(a) Model preparation. (using Data Front End [DFE] software)

(b) Model production. (using Model Production Machine [MPM])

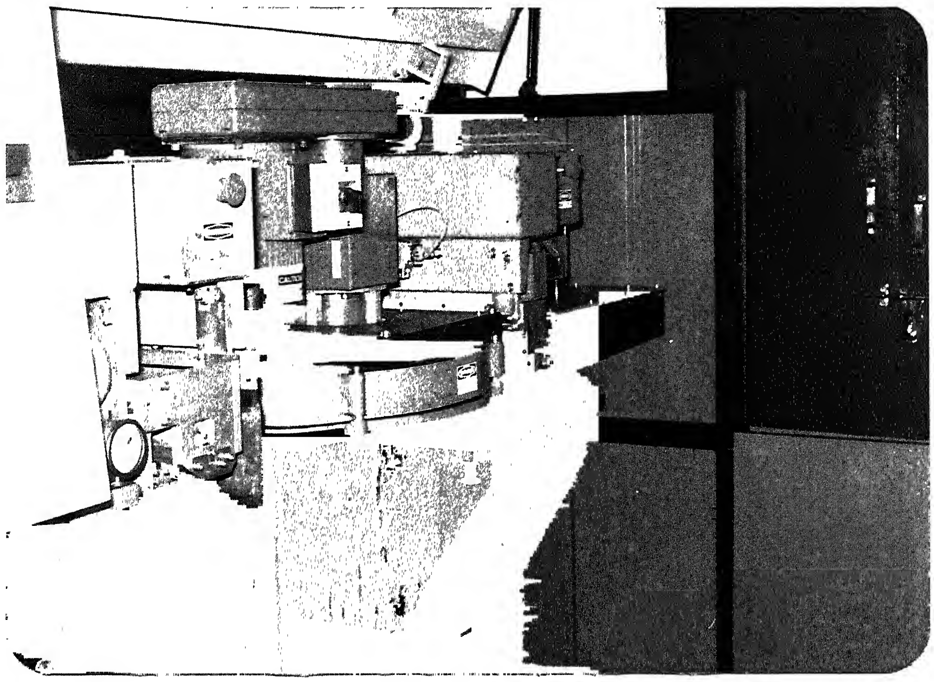
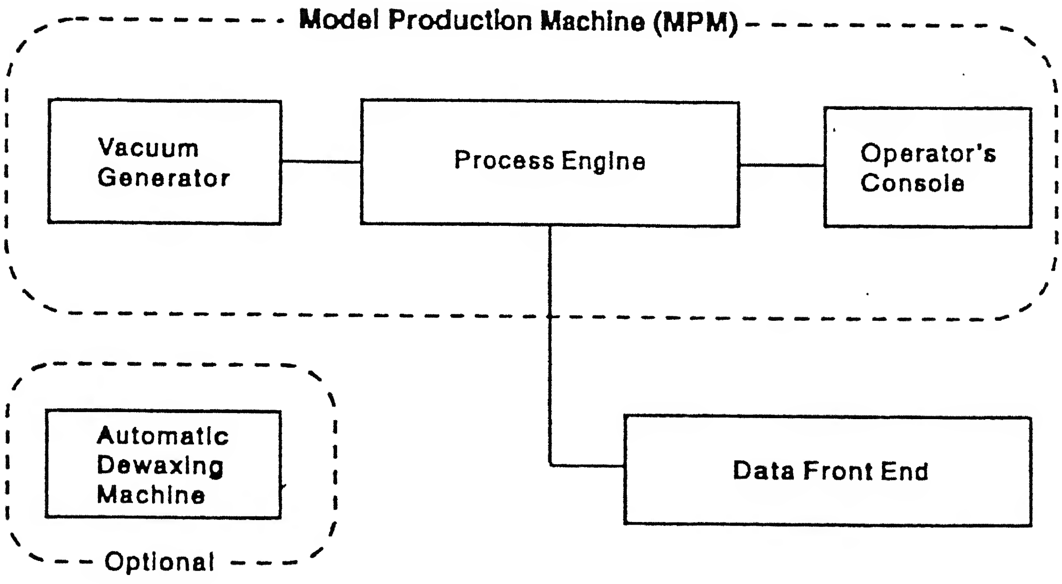


Fig. 2.5 SOLIDER 4600



Solider 5600 System block diagram

Fig. 2.6 Solider block Diagram

2.4.1 Model Preparation

The model preparation is through the graphical user interface provided by Cubital Inc., through the DFE (Data Front-End) software. The different input file formats for the DFE software include STL (Binary & ASCII) and CFL (Cubital Facet List) formats.

The DFE software uses SOLI file format for the internal communication between different stages of the software. The SOLI file is used in the DFE software as it occupies less memory as compared to other file formats. SOLI file uses polygonal facets to represent the outer shell of the solid model.

The DFE software includes a number of model editing and file conditioning tools and is divided into four easy-to-use software modules. It includes (a) Reception (b) Academy (c) Show (d) Production. DFE uses a Theater analogy to describe the process of preparing objects for a production run. The objects in the production run are the "ACTORS" in the show and the Solider workbench is referred to as the "STAGE".

2.4.2 Reception

Reception is used to import 3D part data in industry standard file formats and converts it into a SOLI file used for processing within the DFE software. The import file should not contain any redundant data and it should not have any flaws. If there are any unacceptable physical characteristic like incorrect facet dimensions or missing facets the input file will not be converted into a SOLI file.

2.4.2 Academy

Academy is a Solider DFE application that enables one to improve an actor's physical characteristics and repair the possible flaws in the SOLI file. Academy has four characteristics.

Interfacing: Introducing the actor into the academy and getting the information on its history and current state.

Editing: It involves geometric transformation (rotation and scaling), model Cutting widening and separation of actor items.

Corrections: It includes binding of nearby borders between two items or patching Gaps in items.

Compression: It involves reducing the size of the data required to represent the actor either by uniting facets that are on the same plane, or by uniting nearby vertices.

2.4.4 Show

It collects and organizes a group of actors for a production run on the MPM. The following design goals can be met in SHOW.

a) Maximum number of actors can be placed in minimum height and volume by fitting them together efficiently as shown in Fig. 2.7

b) The surface quality can be optimized by orienting the walls and other major surface of the model parallel to the primary axes of the show volume.

c) It allows creation of complex structure, such as models or casting molds, by combining number of actors into compound assemblies.

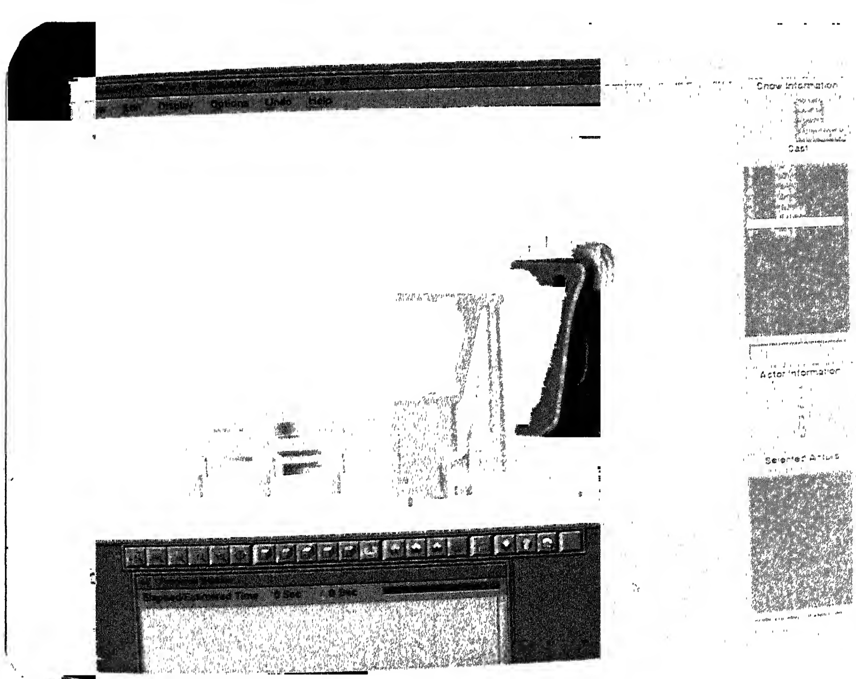


Fig. 2.7 Nesting of actors in SHOW

2.4.5 Production

A application of DFE allows two major operations.

1) **Preview:** This production file to determine if any actors need to be modified or repositioned.

2) **Submit:** This is used to submit the production file to the MPM for production. The data for each layer is stored in a separate file called a CDT (Cubital Data Transfer) file and this is sent to the machine.

2.5 Model Production Machine

The total process of making the model, once the layer data is sent to the machine includes two cycles. The first cycle is the Mask Generation Cycle and the second cycle is the Model building cycle. The various functional units in these two processes are explained below.

2.5.1 Mask Generation Cycle

The entire Mask Generator Cycle is monitored and controlled by the internal computer called the Process Controller. The cycle begins and ends with the Mask Frame underneath the Primary UV Station where a generated mask is positioned above a layer of liquid resin spread on the Model Tray.

The steps in the cycle are (Fig. 2.8):

a. Layer of resin is exposed to UV light.

UV light passes through the transparent areas of the mask, and hardens the resin underneath.

b. Mask removed.

After exposure, the mask Frame moves left to the Toner Unit. While motion, a rubber blade wipes toner off the maylar sheet and collects it for reuse. The Mask Frame moves to the Ionographic Unit where electrostatic charge is neutralized by the Erase Rod. The Mask Frame moves to its extreme left position and stops. There it waits to produce the next mask.

c. Residual charge discharged.

The Mask frame moves right to the Ionographic Unit where electrostatic charge is neutralized by the Erase Rod.

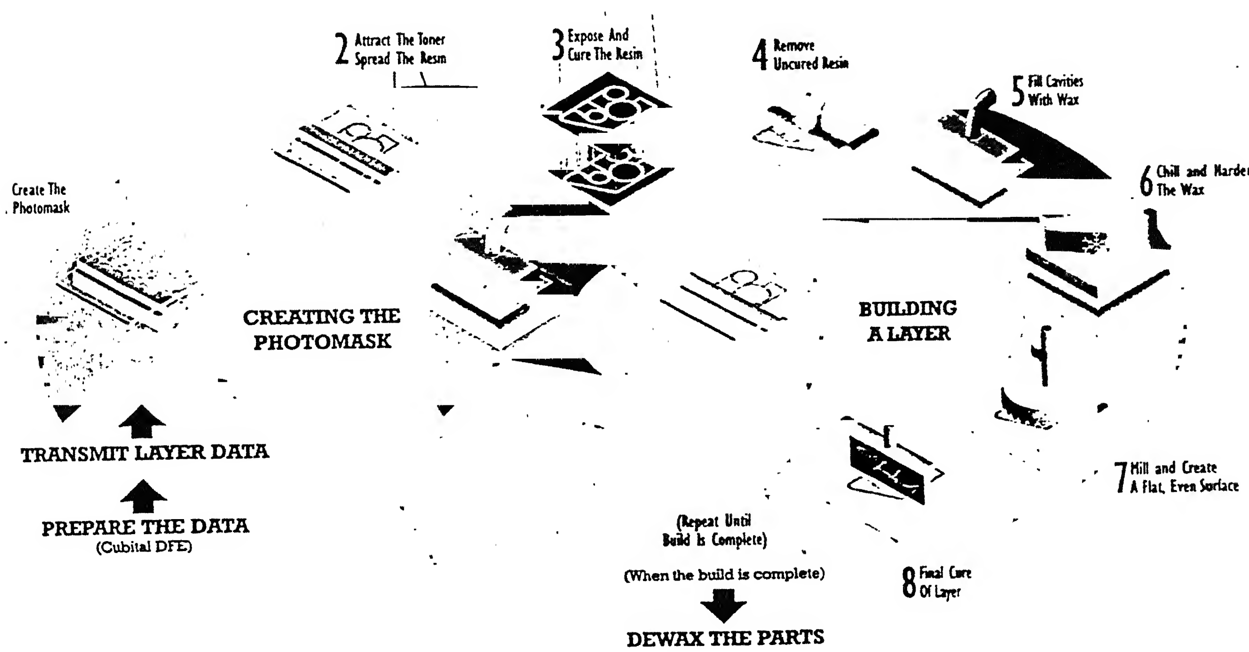


Fig. 2.8 The Solid Ground Curing Process

d. Generation of a latent image pattern.

The Ionographic Unit places electrostatic charge on areas of the Mylar sheet that are to attract the toner. The shape of these areas is determined by the data received from the Process controller.

e. Mask produced.

The Mask Frame with the charge Mylar sheet moves to the Toner station. Toner is attracted to the charged areas of the mask.

2.5.2 Function units

Functional units consists of the following units (Fig. 2.9)

a) Motion Unit: The Motion Unit moves the mask from one station to another. It mainly consists of mask supporting frame, motion track and horizontal motion drive.

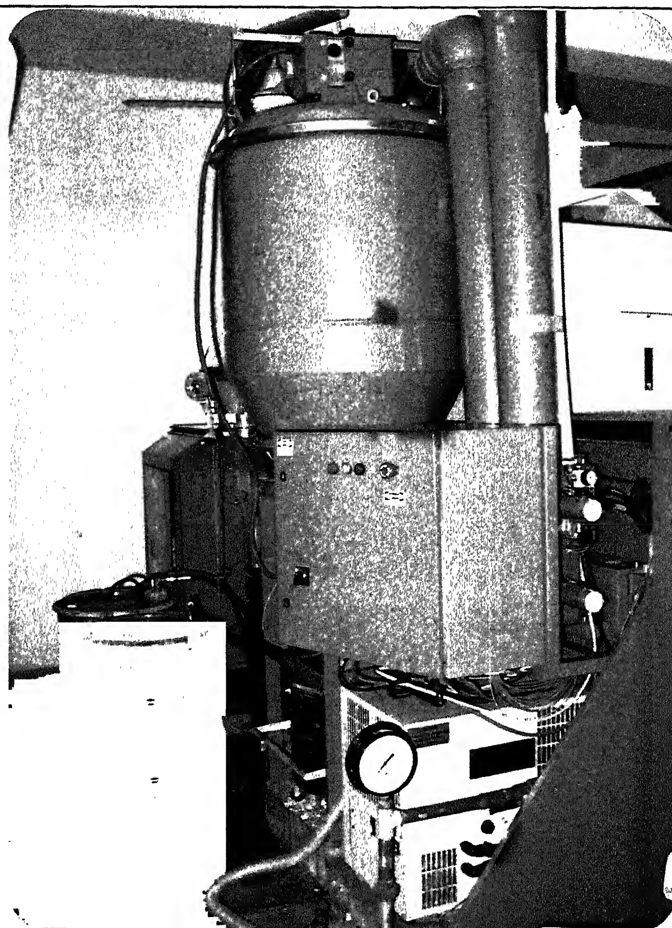
The mask is supported by the mask-supporting frame which is guided through the motion track and driven by the horizontal drive.

b) Mask Unit: The mask determines the geometrical shape of the next layer added to the model. The components making up the Mask Unit are described below. The mask unit consists of a Mylar sheet and a metal-coated glass. Mylar sheet is a transparent sheet on which the mask is generated which stores electrostatic charge that attracts toner to generate the mask. This sheet non-conducting plastic material is glued over the Metal-Coated Glass, which stabilizes the position of the electrostatic charge placed on the Mylar Sheet.

c) Ionographic Unit: The Ionographic Unit neutralizes charges from the Mask Unit and creates an electrostatic image of the next layer on the Mylar Sheet. The major components are:

Erase Rod. It discharged the residual charge from the Mylar sheet. There are six axial wires on the circumference of the cylinder rod. Among these one is active and the other five are idle and are used as spares.

(a) Front View



(b) Back View

Fig. 2.9 Model Production Machine

Ion Cartridge. It jets ions into the Mylar sheet creating an electrostatic image of the next layer. The upper surface of the cartridge contains holes (256 angled rows of 16 hole each) that are fired in a pattern determined by the information received from the Process Controller.

(d) Toner Unit. The toner unit removes the previous mask and develops the next one. After primary exposure, the toner unit wipes toner from the Mylar sheet thereby erasing the previous mask. After the next electrostatic image is on the sheet, toner from the Developed Unit is attracted to the charge areas, creating the mask for the next layer.

2.5.3 Model Builder

The model builder produces a three-dimensional model layer by layer. The shape of each layer determined by a mask generated for that layer. The entire model building cycle is monitored and controlled by the process controller. The cycle begins

and ends at the resin station where a new layer of resin is added. Except during UV exposure, the processing is carried out while the model tray is moving underneath the functional units. The steps in adding a new layer to the model are

1) Layer of resin is added to the model at the resin station. A thin layer of liquid resin is applied.

2) This layer of resin is exposed to UV light at the primary UV station. Model tray moves to primary UV station. The mask, located between the UV light and the model tray, is already prepared with toner to define the shape of the layer. Then UV light passes through the transparent areas of the mask and hardens the resin underneath.

3) After the resin is cured at the UV station uncured resin is removed at the wiper station. An aerodynamic wiper plate creates a strong air jet that lifts off the uncured resin. A suction slit removes the lifted resin, reveling the wax in the model.

4) The remaining resin is cured at the UV station in the secondary exposure. UV light floods the layer to complete the hardening of the resin representing solid areas in the layer.

5) After the resin is taken through the secondary exposure a layer of wax is added to the model at the wax station. A layer of melted wax, that covers the cured resin and fills voids, is then applied with the wax applicator.

6) Wax layer is then solidified at the cooling station. A metal plate cooled by water chilled to 4°C presses down on the wax layer and solidifies it.

7) A new layer is milled to the specified thickness at the milling station. Rotating diamond tipped blades mill away excess wax and resin to leave a layer at the specified thickness.

The model building cycle starts again to produce a next layer. A typical cycle takes 100 seconds to complete a layer.

2.5.4 Functional Units (Model Building Cycle)

The various functional units in the model building cycle are discussed here under (Fig. 2.9).

(a) Resin unit. The resin unit covers the entire upper surface of the Model Tray with a uniform layer of liquid resin. The thickness is adjusted to 160-220 μm in height. The resin unit pumps liquid resin from a storage barrel into the applicator. In the applicator the resin is heated to the required temperature to maintain the viscosity of the resin at a particular value before spreading on the table. The viscosity should not change throughout the process because with the change in viscosity of the resin the thickness of the layer formed on the table changes. For a particular thickness of the layer the exposure time is set to a particular value which depends on the resin properties. With the variation in the viscosity of the resin due to environmental influences the thickness of the resin spread on the table changes.

(b) Primary Exposure Unit. The primary UV unit selectively polymerizes the resin layer by exposure to UV radiation through the mask. The exposed portions of the resin are polymerized and remain on the workplace when the unpolymerized liquid resin is removed by the wiping unit.

UV lamp. A quartz bulb is located in a reflector cavity, which receives energy from a magnetron that generates microwave energy at 2450MHz. The microwaves heat the bulb to create radiation-emitting plasma. The spectral characteristics of the emitted radiation are controlled by chemical additives in the bulb. Protective screens prevent microwaves radiation from escaping to the surrounding area. An igniter bulb in the system to ensure proper starting of the lamp bulb.

Shutter. It is a pneumatically operated system to control the exposure time of the resin to UV radiation.

Magnetron Cooling Interlock. It shuts down the system if magnetron heats up beyond operating temperature. When the magnetron cools down., the system resets automatically and operation can resume.

(c) Wiping Unit.

The wiping unit removes liquid resins from the top surface of the model. The liquid resin left represents 'spaces' in the model layer. The major units of the wiping unit are

Air blower and slit. It produces a thin, powerful stream of air to lift liquid from the surface to roll the wave of liquid resin towards the collector blade and slit. An air pressure gauge and regulator are used to maintain the correct air supply for the blower.

Collector blade and suction slit. It guides the rolling wave of liquid resin into the opening of the slit. The vacuum present at the slit opening extracts the liquid resin from the blade and carries the resin into resin separator.

Resin separator. It separates the liquid resin from the air stream to collect it for reuse and to prevent it from reaching the vacuum unit.

(d) **Wax Unit.**

After the liquid resin not cured during the primary exposure is wiped away, the wax unit spreads a layer of liquid wax approximately 300 µm thick across the entire surface of the model tray. The wax covers hardened resin and fills in void to support the structure of the models during model building cycle. The wax unit

- Melts blocks of wax in the melter
- Stores melted wax and continuously stirs it in a conditioning tank
- Heats melted wax throughout the unit
- Pumps melted wax from the conditioning tank into the applicator
- Lower the applicator 2 mm downward to the spreading height, and after spreading, lifts it back to idle height
- Pushes a volume of melted wax through a slit and spreads it like a blanket onto the upper surface of model tray.

(e) **Cooling Unit:**

The cooling unit rapidly cools and solidifies the wax layer. The cooling occurs by physical contacts between the layer and the cooling plate. The cooling sequence is as follows

- After a liquid wax layer is spread, the model tray moves to underneath the cooling plate.
- The model tray it's position
- The piston moves the inner box downward. When contact is made with the outer box, the inner box pushes the outer downward and chill the cooling plate.
- Both boxes move down and press together on the wax layer. The cooling plate chilled by the transfer plate solidifies the wax.

(f) Milling Unit:

The milling unit mills the layer of solid wax and hardened resin to a finished thickness of 150 ± μm. As the milling proceeds, the milling units sucks chips and dust out of the milling area for disposal.

(g) Vacuum Unit:

The vacuum unit used by the wiper and milling unit. The vacuum generator generates a strong vacuum using an electric motor, which drives a larger turbine. The vacuum manifold switches the vacuum source to either the resin separator or the chip separator line.

2.6 Process Prameters in SGC

(a) Layer Thickness:

We can increase the thickness of the layer to decrease the time taken for the object to be manufactured. But with the increase in the thickness, the surface finish will be reduced due to the staircase effect. Besides this, if the thickness of the layer is increased so should the exposure time of the UV light. Due to increase in exposure time the UV light will pass through the mask covered by the toner particles and solidify the resin, which is outside the required section.

(b) Room Temperature:

The room temperature greatly effects the quality of the model. If the room temperature is less than the prescribed value the viscosity of the polymer increases. Due to the increase in viscosity, the thickness of the layer formed on the table during

spreading increases. But, as there is no corresponding change in the exposure time the energy supplied by the UV light is not sufficient to glue the present layer to the previous one. Due to the weak bounding, the layer is peeled off during wiping and wax is allowed to solidify n these vacated places. Ultimately in the final model, a wax layer is present between the two layers, which reduces the strength of the model.

If the room temperature is higher than the prescribed value, the viscosity of the polymer decreases. So, the thickness of the layer formed during separating decreases, which is less than the final thickness (150 microns) required. The gap is filled with wax and ultimately the strength of the model decreases due to these wax inclusions.

(c) Temperature of Water During Dewaxing

The temperature of the water used to dissolve the wax should be equal to the temperature prescribed, which is set based on expansion ratios given during model preparation. So, by changing the temperature of the water from the prescribed value, dimensional accuracy of the model will be effected.

2.7 Machine Specifications

Gross working volume	500x350x500 mm^3
Dimensional accuracy of model	
Typical	0.5 mm
(measured between targets through the material in any direction)	
Mode resolution:	
X-Y resolution	0.1 mm
Z resolution	0.1- 0.15 mm
Minimum feature size:	
Typical	
Horizontal plane	0.15 mm
Vertical plane	0.6 mm
Gross production rate	1.181x 10^6 mm^3/hr

Model pre-processing time	20 min to 3 hr
Model post-processing time	30 min to 3 hr

2.8 Solider Materials

Solider resins are Acrylic based photopolymers specially formulated for use in the solider model production process. The resins are non-volatile and insoluble in water. Polymerization may be initiated by heat, oxidizing agent, or exposure to UV radiation. The resins are supplied with a polymerization inhibitor, which have limited life-time of six months. There are two kind of resin namely G-5601 and X-607 for making the models. The pattern used in the present work was made of G-5601. The properties of the material are:

LIQUID RESIN	
Viscosity at 32° C	1500
Specific Gravity	1.1 g/ml
CURED RESIN	
Modulus @ 25° C, 50% RH,	600 MPa
Tensile Strength	27 MPa
Flexural Modulus	1010 MPa
Flexural Strength	35 MPa
Elongation at Break	27 %
Thermal Conductivity	0.2 W/m.K

Table 2.2: Properties of G-5601 Resin- Used in Solider Machine

2.9 Patterns Built For The Present Work

The list of the patterns built on FDM1650 machine, the SOLIDER machine which have been used for making the press tool die by using MCP 137 Alloy are given in the table2.2 and Fig. 2.10 shows the patterns made in the FDM and SGC Process.

S. No	Prototype/ Method	Type of Pattern	Slice Thickness (mm)	Build Time (hrs)	Qty.
1	FDM	Singly Curvature Part	0.254		1
2	FDM	Doubly Curvature Part	0.254		1
3	SGC	Singly Curvature Part	0.150		1
4	SGC	Doubly Curvature Part	0.150		1

Table 2.3: Patterns Made on RP Machines

Fig. 2.10: Patterns Made on Different RP Machines

Chapter 3

RAPID TOOLING USING MCP-LOW MELTING ALLOY

3.1 Introduction

It is true that after the development of different RP processes, physical prototype of any complex shape can be made within no time as compared to the conventional processes. But these RP part, can only be used for the visualization, not for the practical use and analysis because these parts material is restricted to only materials like ABS plastics, UV sensitive acrylic, papers etc. Therefore, efforts have been made to further the use of the RP part to manufacture the tools and as a result of these efforts Rapid tooling technology has been evolved. Rapid tooling, a technology that adopts rapid prototyping (RP) techniques and applies them to tool and die making, is becoming an increasingly attractive alternative to traditional machining. The move from traditional machining methods to rapid tooling is more a leap than a step, similar to moving to computer aided design (CAD) from drafting. The rapid tooling technology can develop tool for casting, molding and sheetmetal forming processes using the RP part as pattern.

When effectively implemented within a concurrent engineering environment, RT has the potential to dramatically improve the speed and cost of product development. Using computer-aided design, electronic data transfer, process simulation, and RT technologies, tooling costs and development times can be reduced by approximately 75 percent. RT is useful when tool geometry makes traditional machining difficult because of part complexity or specific geometric features such as undercuts. In the present work, the main idea is to establish the Rapid Tooling process for making a press- tool die. Such a die can be used in a sheet metal forming process. The pattern require to make the die is made from any one of the available RP processes. Also an attempt has been made to develop press-tool to be used for

composite material processing. The MCP Low melting Alloy of HEK GmbH, Germany has been used for making the press tool die. These dies are successfully used for making different types of sheet metal parts and also used for processing different types of FRP composites and unidirectional Glass fiber composites which are indigenously developed at Department of Mechanical Engineering I.I.T. Kanpur.

3.2 Classification of Rapid Tooling

There are several ways in which the tooling can be manufactured rapidly. These are classified into the following two major groups [2].

(a) Indirect RT processes

In these processes, the starting point is the RP component for which the tooling is to be manufactured. The MCP Low melting Alloy process is an indirect RT process in that it needs the pattern, which is made on a RP machine. Others RT processes in this category are MCP Vacuum Casting machine and MCP TAFA machine.

(b) Direct Processes

In these processes the tool is directly manufactured in layers. From the CAD data available, the mold can be designed for a particular component and the resulting mold can be made by any RP process. Direct RT processes are Direct Metal Laser Sintering, Laminated Laser Cut Cavities etc [11].

3.3 MCP-137 Alloy System:

In MCP-137 alloy system, MCP stands for Mineral and Chemical Products and the numeral digits denote the melting point of the alloy i.e. 137° C. This system can be divided into two parts. These are

a) MCP Alloy Melting Tanks
b) MCP Alloy

a) MCP-Alloy Melting Tanks:

The MCP-Alloy melting tanks are used for melting the MCP-137 alloy. It is available in different capacities. The one, which is available at I.I.T. Kanpur CAD-P Lab, has a capacity of 1000 kg or 168 liters alloy MCP-137. It is shown in the Fig.3.1. This electrically heated melting tank has been designed specifically for melting, dispensing and reclaiming MCP-Low melting point alloy. Construction is in steel, and the

melting chamber itself is fabricated in using special grade steel. There are three types of heaters in this tank. These are base heater, side heater and valve heater. The tank is fitted with a hinged lid, with its own handle. The electrical controls are located in a control box, mounted on the tank. The control box is fitted with one voltmeter for checking operating voltage, and with one ammeter for checking the current consumption during heating. There is one elapsed operating-time clock, which gives information on the total length of time that the tank has been in use, though without a record of cumulative energy consumption. It has got a seven-day time switch, using that temperature for both alloy chamber and valve can be pre-set. It is fitted with electronic temperature control and thermocouple sensing. The electronic temperature controllers can be controlled either manually or automatically. The tank is suitable for continuous operation. The working temperatures are from 50 to 220°C and are maintained accurately throughout the whole alloy charge. The tank is double thermally insulated to reduce that loss and improve economy. The main temperature controller guards against overheating the tank and prevents the heating system from exceeding its design temperature. A flexible outlet extension is supplied with every tank. The technical data of this tank are given below in the Table 3.1.

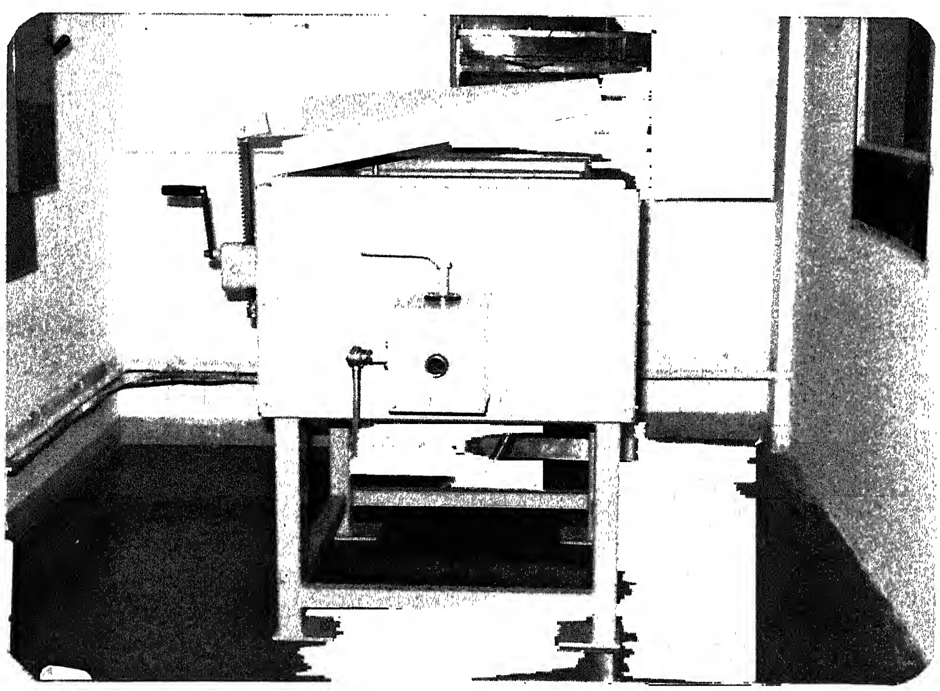


Fig. 3.1: MCP- Alloy Melting Tank

Wattage	18 kW
Base Heater	9.6 kW
Side Heater	6.0 kW
Valve Heater	1.2 kW
Temperature Range	50-220°C
Voltage	230 / 400 Volt
Tank Capacity	1000 kg or 116 l Alloy MCP-137
Weight	680 kg
Temperature Control	Electronic

Table 3.1: Technical Specification of Heating Tank

Operational Details: [12]

After putting the MCP-137 Alloy in the tank, the main switch is turned 'ON'. Then manual control switch is also turned on. In the two electronic temperature controllers, temperatures are set. The first controller, which is for the base and side heaters, is set around 140°C and in the other which is for the valve heater, is set around 155°C. The outlet heater is only for pouring the alloy continuously because its melting temperature is very low so during the pouring time it gets solidified and that interrupts the pouring. Next, the chamber heating is started by means of the "Heaters On" in the control box. Then base heater and side heater switch are turned On. Only at time of pouring the alloy, heater for the outlet i.e. valve heater is turned On. There is provision in the tank for the protection of the tank's heating system that after the value selected on the controller has been attained, the heating is automatically switched off, allowing the temperature to fall back. As the temperature falls below pre-set value, the controller again switches on the supply. In this way, the requisite temperature level will finally be attained. It is possible for the temperature overshot to have an adverse effect on the melting of MCP alloy, and so, when heating the tank from cold, it is advisable not to set the proper temperature straight away, but instead to begin at 2/3 of the correct melting temperature. After the temperature has settled at this level, the value actually required should be entered. There is provision in the

melting tank that its temperatures can be set in the controller for 7 days and that will work automatically. The front panel of the Tank is shown in the Fig.3.2.

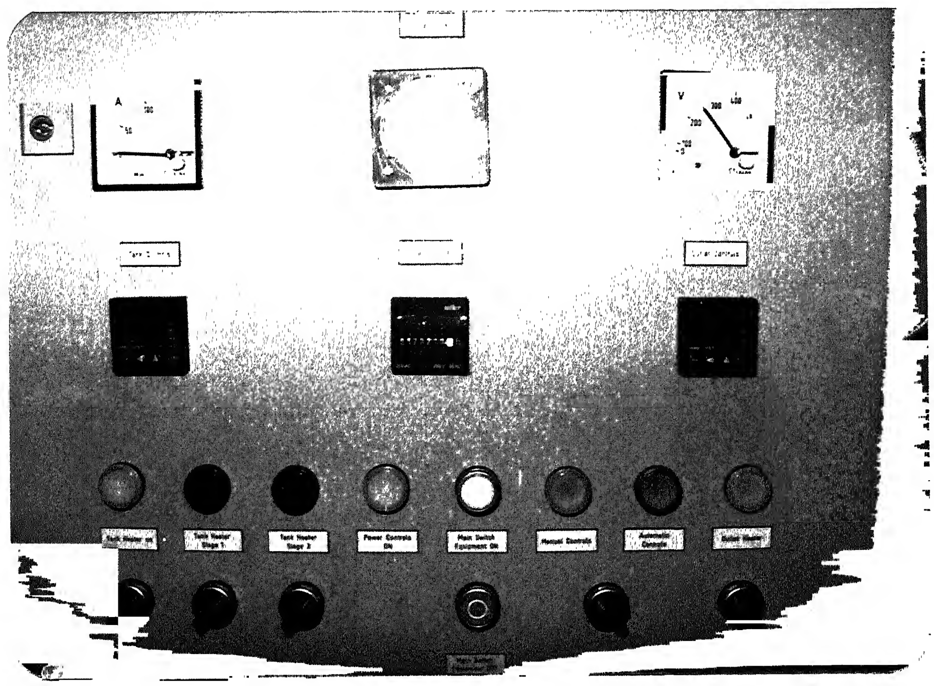


Fig.3.2: Front Panel of The Tank

b) MCP-Low Melting Alloy:

Mineral and Chemical Products, Geneva/ Switzerland developed all low melting alloys. They are composed principally of Bismuth, Tin, and Zinc. Indium is used to obtain an extremely low melting point. By using one or all of these metals a large number of variants can be obtained. Typical melting points are 47, 58, 70, 96, 124, 137, 200, 350°C etc. Since, metal after solidification shrinks. So, Bismuth is added in to the low melting alloy because it shows a volume increase of some 3.3% after solidification. By mixing appropriately with other metals that shrink on solidification, alloys are created whose dimensions do not change on solidification, or which even exhibit considerable expansion. These alloys are relatively hard metals whose strength increases with age. Because the alloys are stable metals, they offer the advantage that they can be repeatedly remelted and used again. These are suitable for normal gravity casting as well as for pressure die-casting and vacuum casting and they can also be sprayed like paints. Their exactness of reproduction is unsuppressed and permits

contours of all kinds to be reproduced. They have very little tendency to stick with other materials. That's why these are ideal alloy for making the press tool die. The physical properties of MCP-137 Alloy are given below in Table 3.2

Density	8.58 g/cm^3
Brinell Hardness No.	23
Melting Point	135°C
Specific Heat (solid, 25°C) (liquid, 160°C)	0.167 J.g-1.°C-1 0.155 J.g-1.°C-1
Latent heat of fusion	49.1 J.g-1
Thermal conductivity	0.185 J.sec-1.cm-1.°C-1
Electrical resistivity	59 μΩ.cm
Viscosity at 135°C	50 MPa.sec
Modulus of Elasticity	15.2 GPa at 35°C
Proof stress, 0.2 % set	31.1 rising to 42.1 MPa
Tensile strength	60.1 rising to 62.3 MPa
Elongation (% in 5.65 $\sqrt{A}$)	80 falling to 66
Compressive strength	41.6 rising to 46.7 MPa
Poisson's Ratio	0.33

Table 3.2: Physical Properties of MCP-137 Alloy

3.4 Process of Die Making

3.4.1 Preparation of The Pattern

MCP 137 an alloy that reproduces the surface accuracy or inaccuracy exactly. It has very good releasing properties. Sufficient care should be taken during the preparation of the pattern for making the press tool die, when the pattern is made on the various RP processes because layers impression comes on the tool surface which will effect the end part accuracy. This precaution is more necessary when the pattern is made on the FDM machine because FDM parts has porosity, which is detrimental to die making. MCP 137 alloy enters in these pores and it becomes very difficult to

pattern from the die and it also copy's the impression of the layers on the die surface. Hence a lot of care should be taken in preparing the pattern. The pattern is to be thoroughly cleaned and filed with emery paper to get smooth surface on die. If necessary some times metal spray can be done on the pattern to get surface finish like metal.

3.4.2 Casting of MCP 137 Alloy

There are different ways of casting the MCP 137 alloy to make the press tool die and punch from the existing pattern. But, if pattern is made on Rapid Prototyping machine then there are only two ways of making the press tool. In this work both these two methods have been employed and are explained below. These two methods are:

- **i)** Two-part press tool
- **ii)** Three-part press tool

(A) Casting Frame

The casting frame is common to both these two processes. It can be made of wood, ABS or laminated chipboard but it should be able to withstand the temperature around 150°C and the force exerted on the sidewall of the frame due to the alloy. The size of the frame depends on the pattern size. There is no any hard and fast rule for the calculation of the size. But in general, if the component dimensions are X*Y*Z mm the casting frame dimensions should be (X+60)*(Y+60)*(Z+90) mm. The extra height on the frame is needed for the safety purpose.

(I) Two Part Press Tool:

This two-part press tool can also be made by two methods.

(a) Using Wax Sheet
(b) Without Using Wax Sheet

(a) Using Wax Sheet :

(1) Casting of The First Half of The Tool (Punch):

This part is common to all the different type of processes and same as the conventional casting process. The pattern included with guide pins is kept on the

tooling board and the side frame is kept around the pattern then forming sand is filled in to the box and rammed properly. Box is then put in the inverted position and pattern & side frame are removed. Another side frame with larger height is kept all around it and on the top of it cover plate fixed with all fixtures needed to attach the tool on the press, is attached. Then MCP 137 alloy is poured in to the box completely. After solidification of the alloy, the box is again kept in to the original position and forming sand is removed from the box and the upper surface of the first half of the tool (i.e. punch) is cleaned and filed to get the good surface finish.

But since here casting is done directly in the mould through pipe, so, there is possibility that during pouring time the mould gets distort which will affect the accuracy of the tool. Here an alternative method is possible which is developed by the author i.e. instead of casting the alloy in sand mould, casting should be done in the plaster mould. For making the plaster mould for one half of the tool, the process is same like as discussed above only difference is that in place of pouring Low melting alloy in to the box, first Plaster of Paris is poured. After solidification, the pattern is removed and then wax sheet around the surface of the plaster mould is glued up to the thickness of the sheet metal or composites which have to be processed on the tool and then the mould is again kept back in the box. Low melting alloy is poured in the box and after solidification of alloy wax sheet is removed and tool is cleaned. There are two other advantages of this process. First one is that due to casting in plaster mould the surface finish is very good. The next one is that when pattern made on Solider machine is used then there is no chance of any distortion in the tool because when Solider pattern is used directly then due to its poor heat bearing capacity it becomes too flexible at temperature around 130°C which affect the tool accuracy.

(2) Casting The Second Half of The Press Tool (Die):

The upper surface of the first half of the tool is covered with the wax sheet to the thickness corresponding to the required part thickness which is to be made using the tool for sheetmetal part or composite part. At this stage an alternative is possible that a steel drawing ring can be integrated in to the base tool to increase the tool life. Then second half of the tool (i.e. die) is cast.

Now, the press tool is ready to produce the parts.

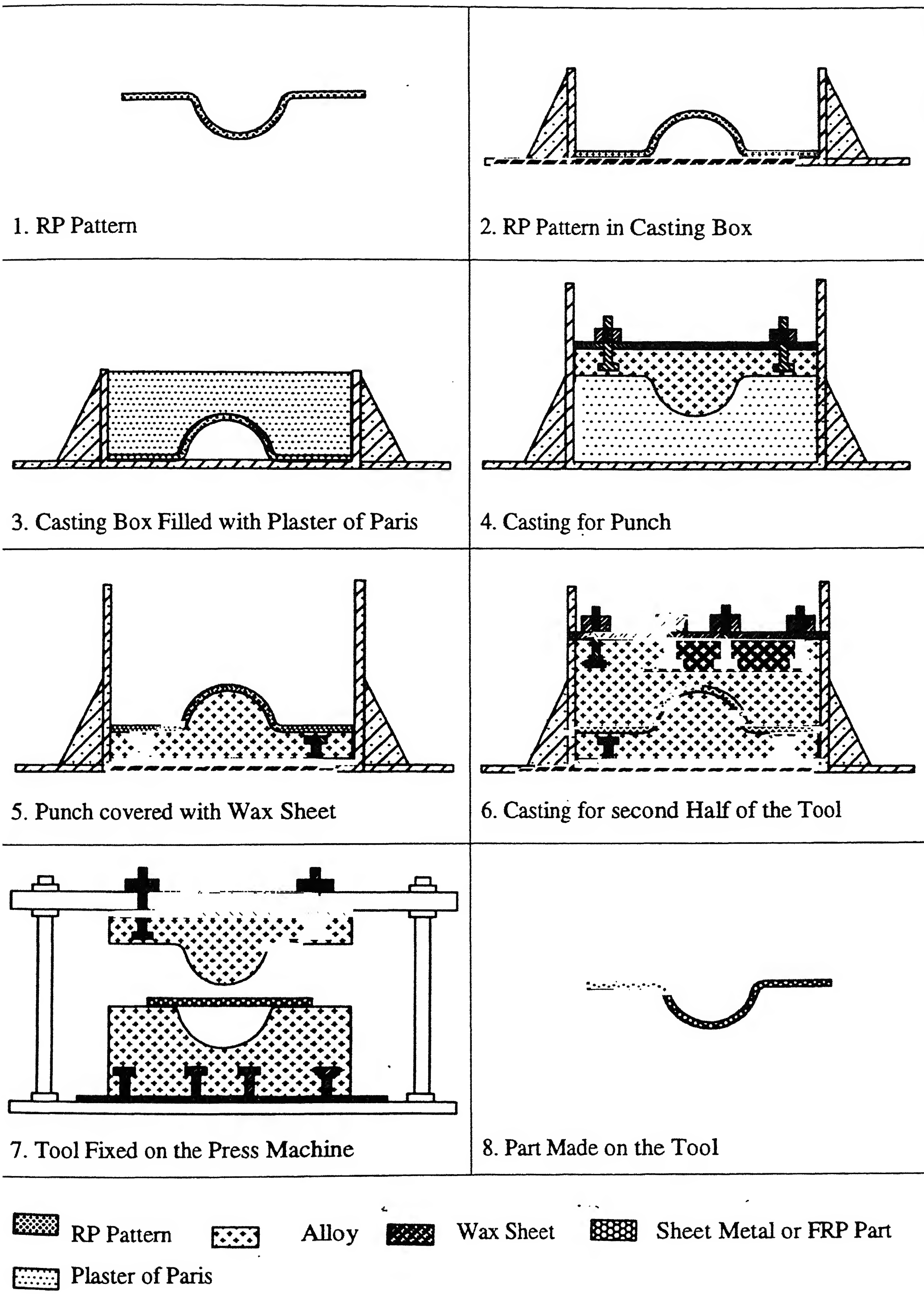


Fig. 3.3: Process of making two-part Press-Tool using Waxsheet

(b) Without Using Wax Sheet:

In this process any part i.e. punch or die can be made first. First the pattern included with guide pins is kept on the tooling board. Then frame all around the pattern is kept. At the top of the frame, a tooling board fixed with all fixtures, which are necessary for attaching this tool on the press machine, is kept. After that alloy is poured completely in to the box. After solidification of the alloy, the box is kept in to the inverted position and the top tooling board is removed and same process is repeated for the second half without detaching the pattern form the first half. Then the two half is opened and pattern is removed. Some cleaning work is done on the tool surfaces then the tool is ready for production of parts.

The Whole process is shown in the Fig. given below.

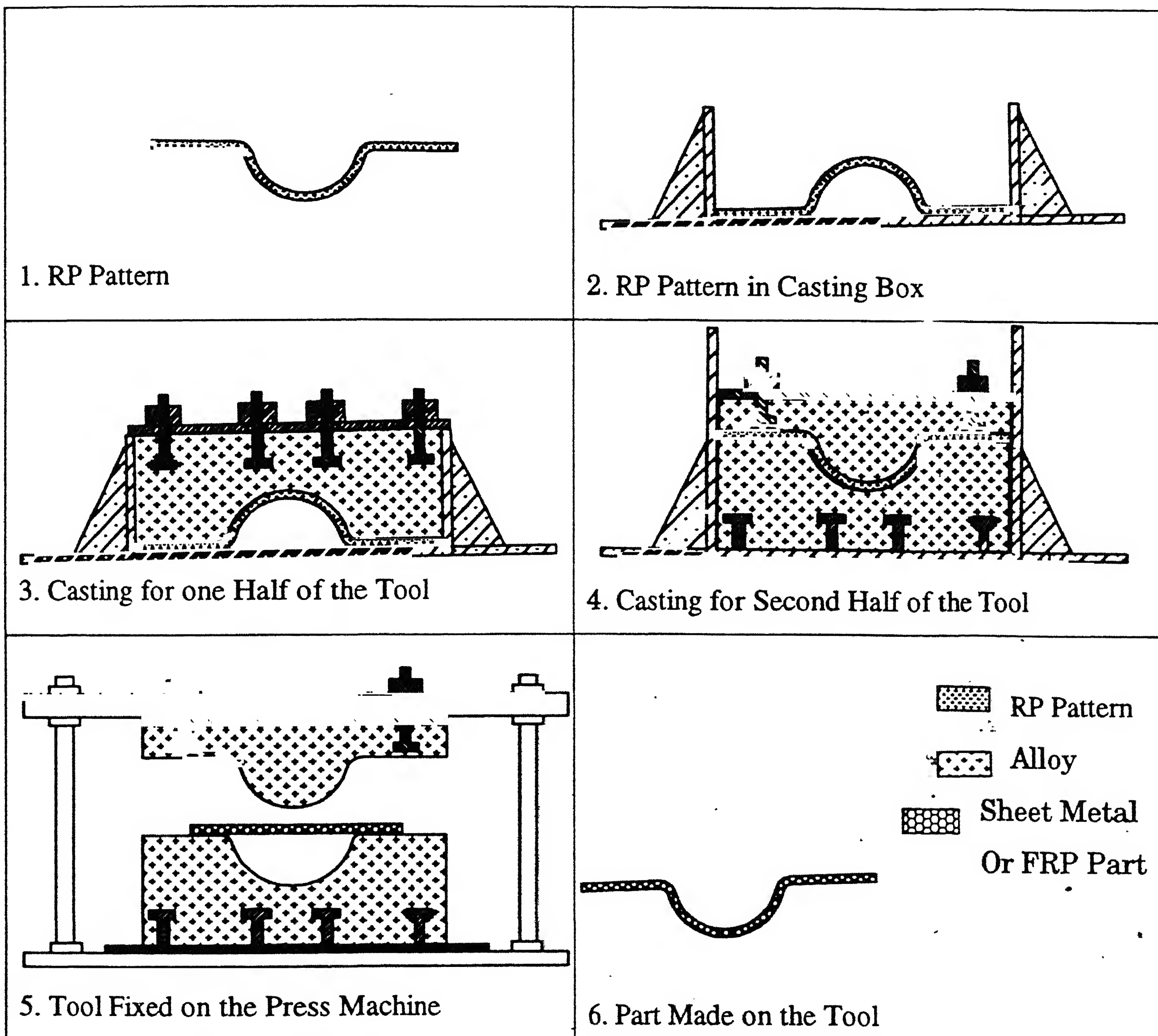


Fig.3.4: Process of making two-part Press-Tool without using Waxsheet

(ii) Three Part Press Tool:

In this type of tool the blank holder is not integrated with the punch. This three-part press tool is generally made for the big part. It can also be made by two methods. These two methods are:

(a) Using Wax Sheet

(b) Without Using Wax Sheet

(a) Using Wax Sheet

(1) Casting of the first half of the tool(punch) & blank:

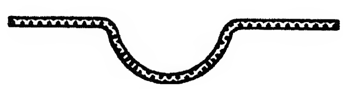
This part is common to all the different type of processes and same as the conventional casting processes. The pattern included with the guide pins is kept on the tooling board and the side frame is kept all around it. After that, forming sand is filled in to the box and rammed properly. Another tooling board is fixed on the top of it. Then the box is kept in to the inverted position and tooling board along with side frame is removed. Another side frame with lager height is kept all around it and metallic frame around the cavity is inserted and then outside the cavity is filled with the forming sand just for the support. At last, top frame with all fixtures which are necessary to attach this punch to press is needed is fixed and then low melting alloy is poured. After solidification, the metallic frame and the forming sand both are removed and the punch sidewall is coated with the wax sheet according to the desired thickness then low melting alloy is poured to get the blank holder. After solidification the whole box is kept in to inverted position and forming sand as well as pattern is removed. At last the surface is cleaned and filed properly to get the good surface. Here also plaster mould process can be used.

(2) Casting of the second half of the tool (Die):

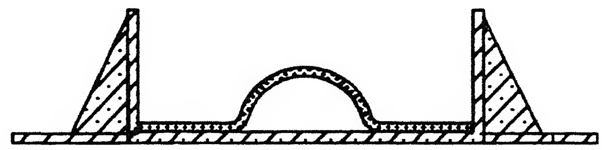
The upper surface of the punch and blank holder is covered with the wax sheet up to the required thickness. At this stage an alternative is possible that a steel drawing ring all around the cavity i.e. on the blank holder surface can be fixed to increase the tool life. Then side frame around it is kept and on the top of it toolboard with all fixture

attached is fixed then low melting alloy is filled. After solidification some cleaning work is required then the tool is ready to attach on the press machine.

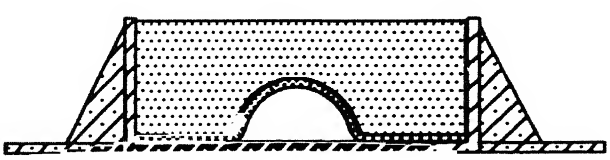
The whole process is shown in the figures given below.



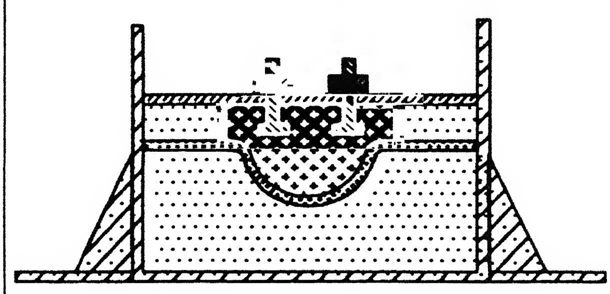
1. RP Pattern



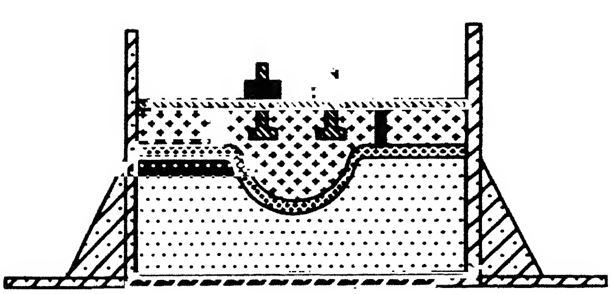
2. RP Pattern in Casting Box



3. Molding Box Filled with Plaster of Paris

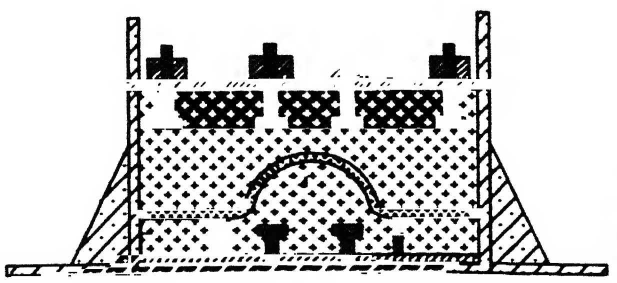


4. Casting for Punch

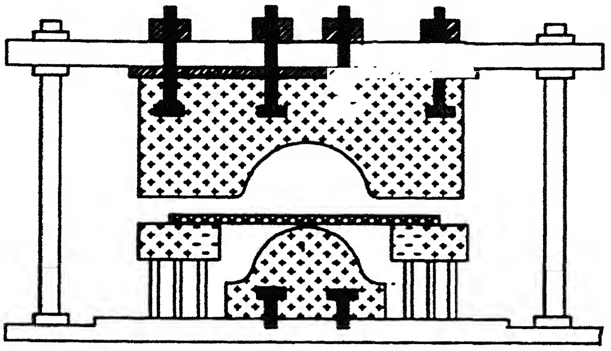


5. Casting for Blankholder

6. First Half Covered with Wax sheet



7. Casting of Second Half of the Tool



8. Tool Fixed on the Press Machine

9. Part Made on the Tool

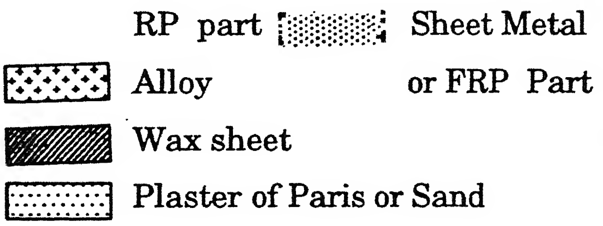


Fig. 3.5: Process of making three-part Press-Tool Using Waxsheet

(b) Without Using Wax Sheet:

(1) Casting of first half of the tool (Punch & Blankholder)

First the pattern included with guide pins is kept on the tooling board. Then side frame around the pattern is fixed. Forming sand is filled in the box and rammed properly. Another tooling board is fixed on the top of it. Then the whole box kept in the inverted position. Previous side frame replaced by the larger height frame. All around the cavity a steel frame is kept. Out side of the steel frame space is filled with forming sand. A tooling board fixed with all fixtures is attached to the side frame top. Then low melting alloy is poured completely in the box to get the punch. After solidification, forming sand is removed from the out side and alloy is poured to get the blankholder

(2) Casting the second half of the tool (die)

The box is kept in to the inverted position and sand is removed. Then without removing the pattern alloy is poured in the box to get the die.

The whole process is shown in the figures given below.

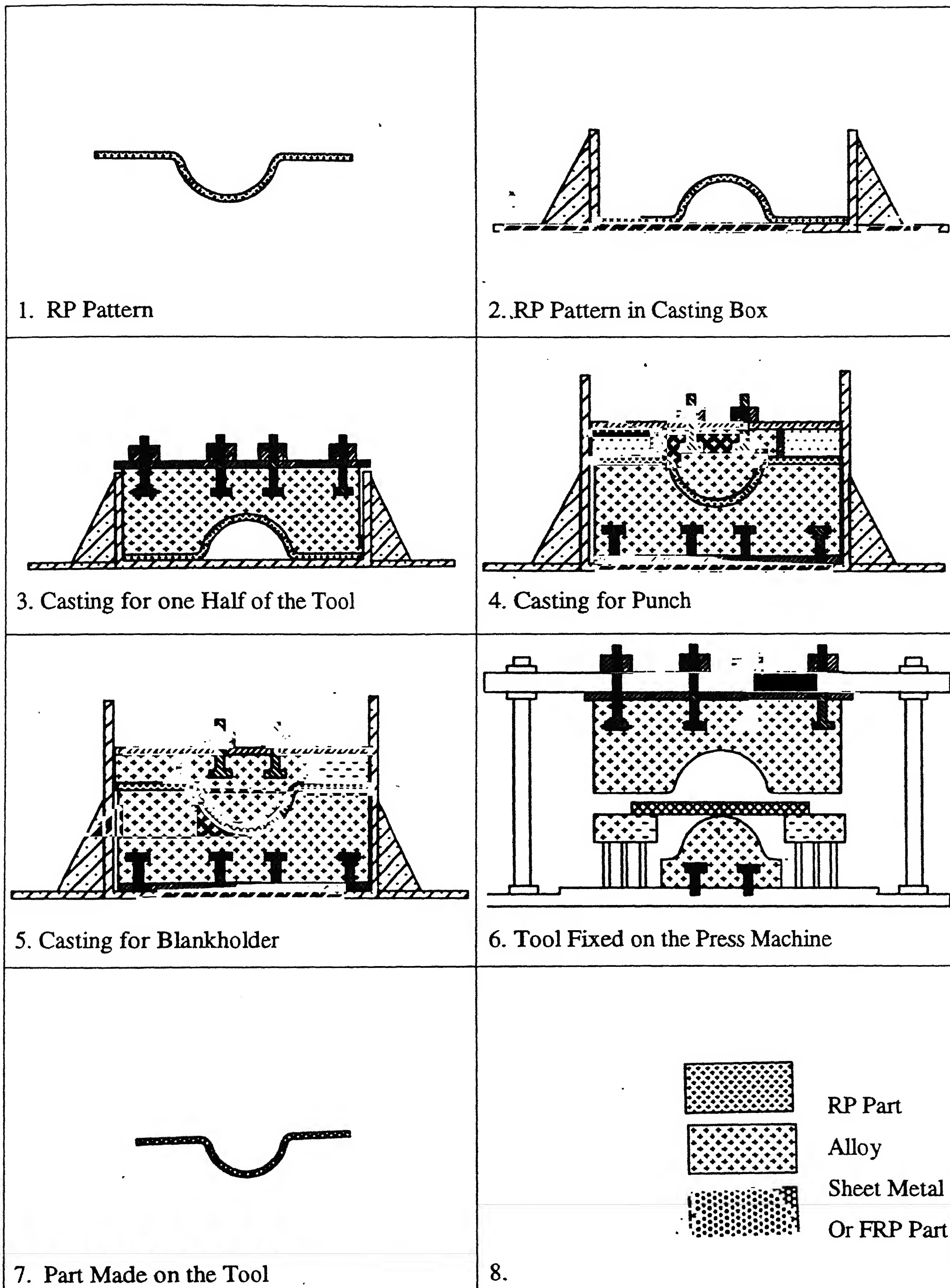


Fig. 3.6: Process of making three-part Press Tool without Using Wax Sheet

3.4 Application of The Press-Tool

The Press-tool die has been successfully used for making the different types of FRP composites parts made of from glass fiber cloth, short fiber and prepreg. The processes of making the FRP parts has been explained below.

(a) Fabrication of FRP composites using fiber clothe or short fibers:

First of all on the die surface some release agents (like Silicone release agent, PVA, Teflon sheet etc.) are sprayed properly. Then alternately, manual lay up of epoxy with hardener and glass fibers (either in cloth or short fiber form) has been done. The die with the punch is kept under pressure of 6-7 Ata in the hydraulic press for 8 hours. After that the part is separated form the die.

Here, it has been found that silicone release agent works fine for this purpose and Teflon sheet can not be used for double curvature die.

FRP Parts made from fiber cloth and short fibers on MCP-137 Alloy die have been shown in Fig.3.7

Fig. 3.7: FRP Parts Made on MCP-137 Alloy Die using Fiber cloth or Short fiber

(b) Fabrication of FRP composites parts using prepreg:

In this process also, firstly silicone release agent is sprayed on the die surface. Then alternate layer of epoxy with hardener and prepreg is lay up manually up to the predetermined layer. Here, the prepreg can be lay up on any desired orientation as per the required strength. Then, the die with punch is loaded on the hydraulic press and heated up to the 120° C. Pressure of 6-7 ata is applied on the press tool. The temperature of the die is maintained at 120°C for 6-7 hours. Then the component is separated from the die and kept for post curing at 155°C for 2-3 hours.

Here, it has been found that making parts out of prepreg is very difficult. Because none of these release agents found to be good and since the melting temperature of the die material is 137°C so, maintaining temperature of 120°C is difficult.

FRP parts made from unidirectional prepreg on Rapid tooling die have been shown in Fig.3. 8

Fig.3.8: FRP Parts made on MCP-137 Alloy Die using Prepreg

3.5 Other Application of MCP-137 Low Melting Alloy

There are many other uses of MCP-137 Low melting alloy.

(1) Cores made from this alloy can be used in MCP-TAFA system in injection molding process. It is shown in the Fig.3.9 below.

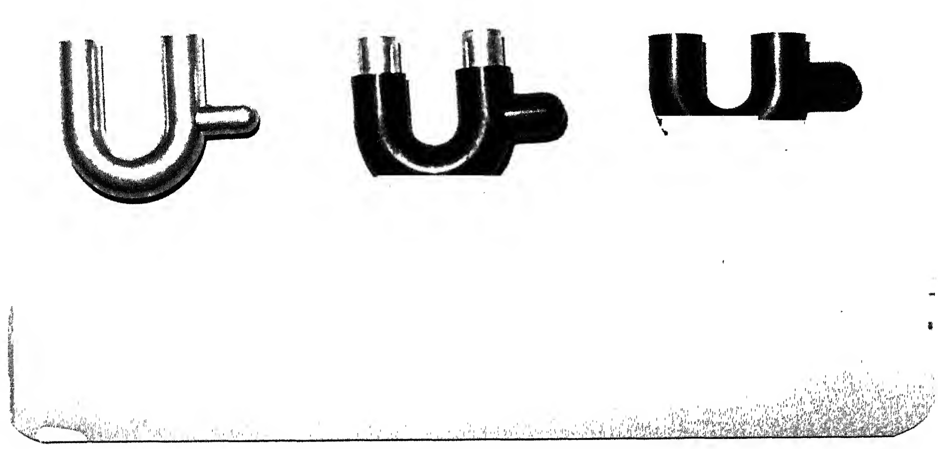


Fig.3.9: Use of Core Made from MCP-137 Alloy in Injection Molding

(2) This low melting alloy can be directly poured into the mold made from Silicone rubber and that part can be used for various purposes. This is shown in the Fig.3.10

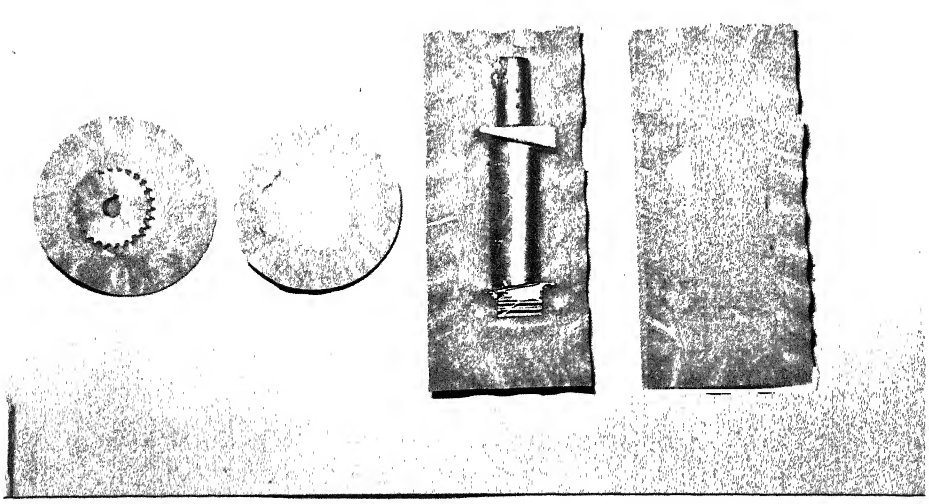


Fig. 3.10: Parts Made from MCP-137 Alloy in Silicone Mold

Chapter 4

FINITE ELEMENT ANALYSIS

4.1 Introduction

Finite Element Method is a powerful numerical technique to get approximate solution for problems of continuum mechanics. Inherently it is approximate, since a continuum with infinite number of degrees of freedom is replaced with a discrete system with finite number of degrees of freedom. The continuum is broken into a finite number of regions called elements, connected at finite number of points called node [18]. An approximate admissible solution is constructed over the assemblage of elements, and the solution continuity is maintained at the inter-element boundary.

4.2 Linear Static Analysis

In linear static analysis loads may consists of concentrated nodal forces, non zero specified displacement, thermal loading and body forces due to gravity, angular velocity and angular acceleration.

The total potential of an elastic body under general loading may be defined by

$$\Pi = U + V \tag{4.1}$$

Where

U is the strain energy of the body and

V is the potential energy of the applied load

The principal of minimum potential energy states that among all the admissible field u, which satisfies the prescribed kinematic conditions, the actual displacement is the one that makes the total potential energy stationary. Therefore Eq. 4.1 gives

$$\delta \Pi = \delta U + \delta V \tag{4.2}$$

Where

$$\delta U = \int_V \sigma^t \, \delta \varepsilon dV \tag{4.3}$$

$$- \delta V = \int_V \delta u^T \, bdV + \int_A \delta u^T t \, dA + (\delta u)^T p_c \tag{4.4}$$

Where

u and c list the components of the stress and strain tensor in a vector form

b is the body forces and

t is surface traction vector

u is displacement vector

$\bar{u}^c$is a vector listing the displacement components corresponding to the concentrated forces.

Mathematically,

$$\sigma^t = [\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{yz}, \sigma_{zx}] \tag{4.5}$$

$$\begin{aligned} \varepsilon^t &= [\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, 2\varepsilon_{xy}, 2\varepsilon_{yz}, 2\varepsilon_{zx}] \\ &= [\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \gamma_{xy}, \gamma_{yz}, \gamma_{zx}] \end{aligned} \tag{4.6}$$

$$b^T = [b_x, b_y, b_z] \tag{4:7}$$

$$t^T = [t_x, t_y, t_z] \tag{4.8}$$

$$u^T(x, y, z) = [u_x, u_y, u_z] = [u_1, u_2, u_3] \tag{4.9}$$

Equations 4.2 through 4.4 indicates that for an arbitrary virtual displacement δu satisfying the prescribed kinematic boundary conditions, the virtual work done by the internal forces is equal to the virtual work done by the external forces. This is exactly the principal work. It is important to note that the principal of virtual work holds for any kinematically admissible virtual displacements and it is independent of the material stress-strain relationship. In finite element analysis, a continuum is discretized by a number of suitable finite elements, which are interconnected through nodal points on the boundaries of the elements. The total potential of the continuum Π, may be considered as the sum of the individual element contributions Π^e so that

$$\Pi = \sum_{e=1}^{m} \Pi^e \tag{4.10}$$

Where

m is the number of elements.

The following steps are essential in a typical FEM formulation.

4.3.1 Discretization and approximation

This is the mesh generation step. Here depending on the nature of the problem element type is selected and their number controls the convergence. Too coarse mesh will give inaccurate results whereas a very finer one will take lot of CPU time to solve. The type of approximating function is also selected in accordance to the nature of the problem. Using these information's so called shape functions or interpolating functions are found out.

4.3.2 DOF per node and Boundary Conditions

Every element has associated Degrees of Freedom to its nodes. It could be transnational and/or rotational. The boundary conditions are decided by the physical modeling of the real life problem.

4.3.3 Formulation of Elemental Matrices and their assembly

By knowing the material properties, DOF and the load, elemental coefficient matrix, DOF matrix and elemental right side vectors are formed. This is evaluated for each and every element. After formulation, the elemental matrices are assembled and global matrices are formed. The final form will be as shown below [18].

$$[K]\{\Delta\} = \{F\}$$

Where, [K] is global stiffness matrix

$\{\Delta\}$ is the displacement vector

{F} is the global right side vector

4.3.4 Applying Boundary Conditions

After assembly the boundary conditions are forced on the global matrices and a sparse matrix is prepared.

4.3.5 Model Solution

The sparse matrix is then solved using any robust numeric scheme.

4.4 Problem Formulation

4.4.1 Restraints

The die would be rigidly fixed to the platform of the press machine and hence the bottom surface will have fixed boundary conditions.

4.4.2 Force modeling

Three types of press-dies have been taken for the stress analysis. The stress analysis of these dies have been done for different applications like for FRP composites processing and sheet metal forming process. The main idea behind the analysis is that to find the suitability of the press-tool for different application. Therefore, according to the application of the dies, forced are applied.

1) Force modelling for FRP Composites Processing:

Two types of press dies have been taken for this analysis. One is singly curvature die and the other one is doubly curvature die. Two types of FRP composite parts have been made, using these tools. One part is made up of glass fiber cloth and epoxy and other one is made up of unidirectional glass fiber (prepreg) and epoxy. For making FRP parts simple uniform pressure are applied on the die surface.

2) Force modelling for Sheet metal component:

Analysis of one simple press–tool die for shallow drawing of cylindrical cup made of different sheet metal has been done. The forces on the dies are applied for different types of sheet metal like Aluminum, Steel etc.

4.4.3 Material Properties

MCP 137

The properties of MCP 137 as given by manufacturer are as below:

Tensile Strength	62.3 MPa
Poisson's Ratio	0.33
Tensile Modulus	15200 MPa
Density	8.58 $Kg\ m^{-3}$
Thermal Conductivity	18.5 $Wm^{-1}K^{-1}$

Table 4.1: Mechanical Properties of MCP –137 Alloy

4.5 I-DEAS Simulation Tool

I-DEAS Master Series ™ is trademark of "Structural Dynamic Research Corporation (SDRC)". It is a well-known package for solid modeling. It comprises of many modules for manufacturing applications, finite element simulation, rapid prototyping and so on. I-DEAS Master Series TM simulation tools provide access to powerful geometry construction and editing capabilities, extensive capabilities for building models, and a wide selection of solutions to simulate real world conditions. The whole package is built with concurrent engineering concept. So at any time if the original design changes automatic updating of finite element model is done. It implies that at a later stage the design changes, the mesh will get updated and also the boundary conditions. Moreover the software handles boundary conditions by geometry rather than by nodes and elements. This makes the process of applying loads and restraints very simple.

Important features of simulation include:

- Geometry tools
- Modeling tools
- Integrated solvers
- Post processing tools

The figure 4.1 shows how a solid model can become a finite element model.

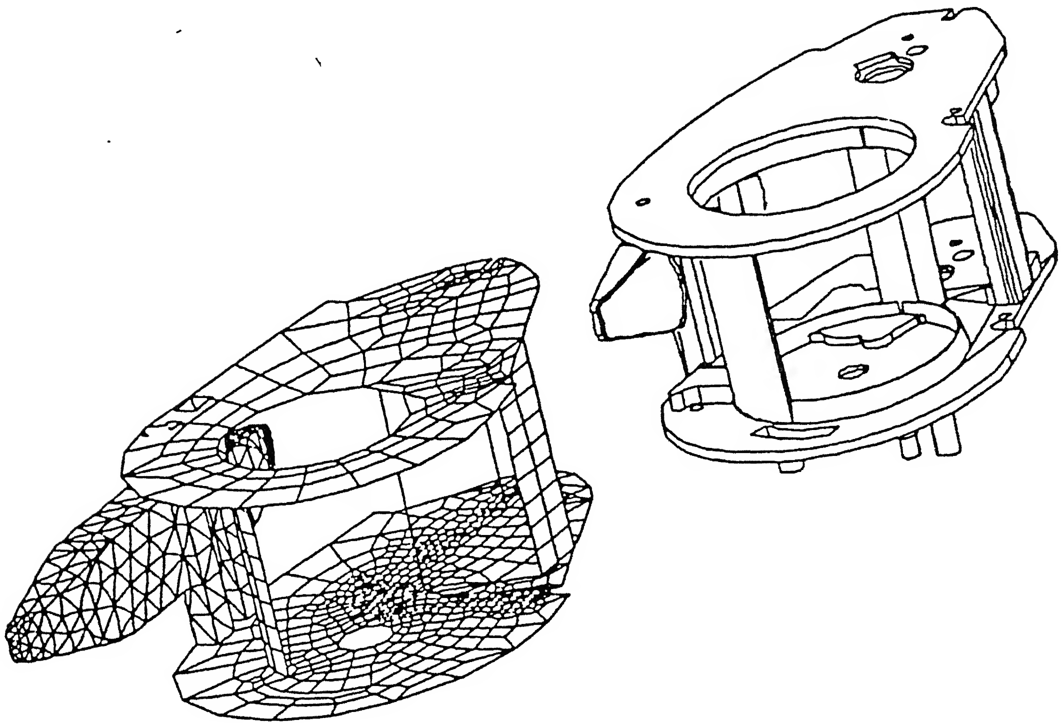


Fig. 4.1

4.5.1 Geometry Tools

The I-DEAS Master Series software uses the master model directly for simulation. The non-manifold topology foundation of the software allows usage of wireframe, surface and solid geometry at any time, as appropriate for model building.

4.5.2 Modeling Tools

Having prepared the geometry appropriate for analysis, a finite element model has to be generated. Below is a brief discussion on these tools. More details can be found elsewhere [20].

Solid elements predict 3D stresses accurately. Modeling them is also simple. But they need intensive computations. Thin-shell elements and beam elements are abstractions of the 3D physical model. Thin-shell elements are abstracted to 2D elements by storing the third dimension as a thickness on a physical property table. Beam elements are abstracted to 1D elements by storing the 2D cross-section as separate beam section property. Each level of abstraction takes more preparation time, but reduces the solution time. Understanding the behavior of each element type helps to make the best modeling decisions. In the present work solid elements are used.

Within this category I-DEAS supports either brick or tetrahedron element with different orders. But as tetrahedron elements are better for geometrical mapping it is chosen. A diagram of the element is shown here.

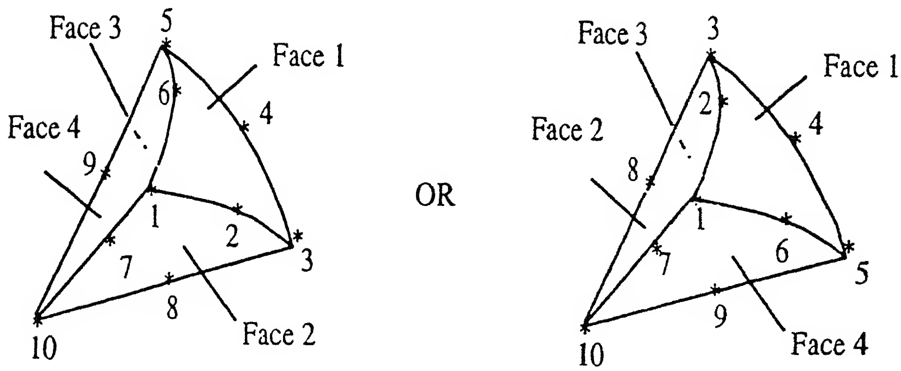


Fig. 4.2 Solid Parabolic Tetrahedron Element

Topological Data:

- Nodes = 10
- Faces = 4
- Nodal DOF = 3 transnational degrees of freedom assigned to each node.

4.5.3 Integrated solvers

I-DEAS has different in built solvers for different kind of problems. Some of them are I-DEAS Master Solution - Linear™, I-DEAS Master Solution-Nonlinear™, I-DEAS TMG™, I-DEAS System Dynamics Analysis™ and so on. The solution algorithm includes both sparse matrix and iterative solver. Apart from this it interfaces with external solvers like ABAQUS™, ANSYS™, Cosmic NASTRAN™ also.

4.5.4 Post Processing Tools

Understanding the results is the most important and critical task in a Finite Element analysis. Without good interpretation, even an accurate solution will be futile. The Post Processing Task and the IDEAS Visualizer™ provide a wide range of

movie files could be prepared with the results. So animations can be stored for future applications as a standard movie file.

4.6 Analysis

4.6.1 Geometric Modeling

Stress analysis of three geometrically simple press- tool dies have been done. First the two axisymmetric parts have been made by surface revolution of the cross section. With these parts dies have been created using Boolean operation and then filleting the corner of the die and punch in the simulation module of I-DEAS Master Modeler™. Dimensions of the spherical die is 150 X 150 X 40 mm^3 and dimension of the cylindrical die is 160 X 160 X 55 mm^3. The third part first made by extrusion and then same method is used as for previous dies for making the die. The dimension of this die is 155 X 140 X 60 mm^3. The wire frame figures of all these dies are given below.

The dies are shown in Fig. 4.3

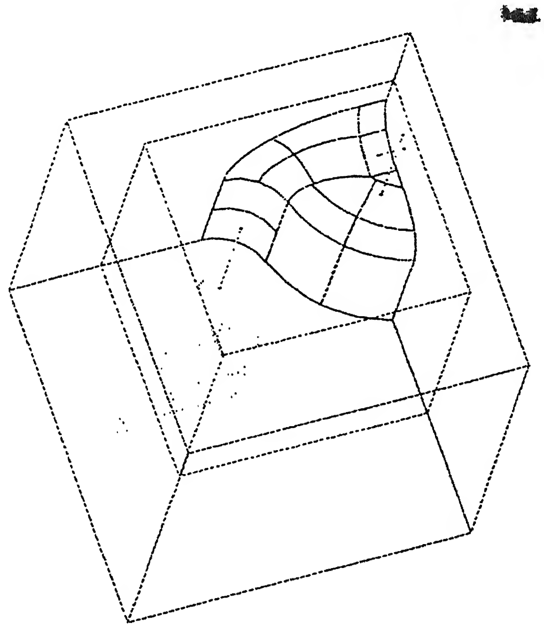


Fig.: 4.3.1

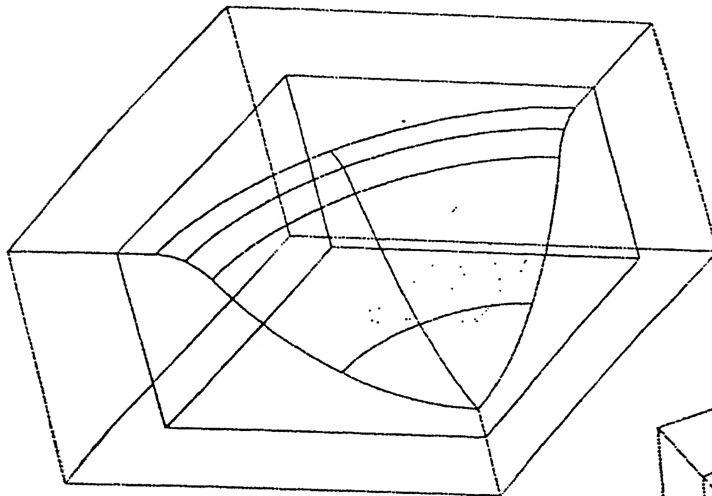


Fig.: 4.3.2

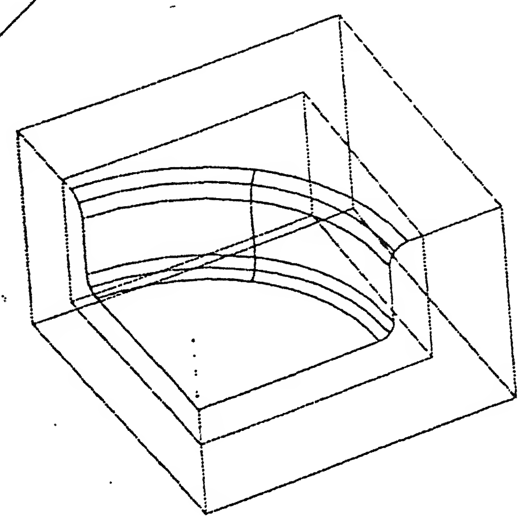


Fig. 4.3.3

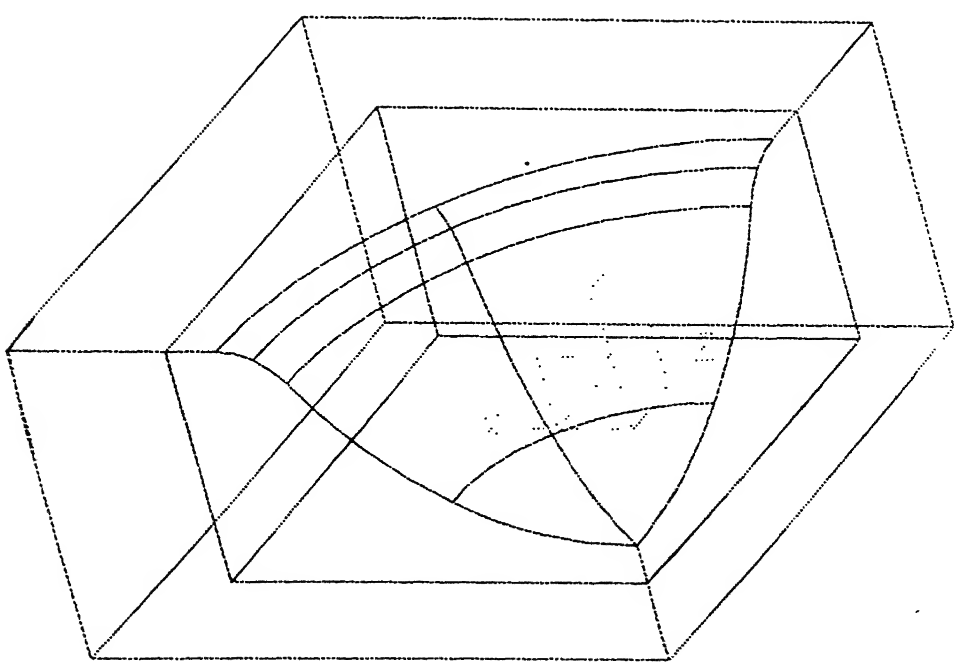


Fig. 4.4: Die for the Doubly Curvature pattern shown in Fig. 4.3.2

4.6.2 Boundary conditions

As explained in the section entitled "problem formulation", the loads and restraints are applied on according faces. Interestingly there exists symmetry in both geometry and loading. Thus, the die is thus split into four halves and only one such half is used for analysis. This is to reduce the computation time. This essentially dictates that the bottom face is totally arrested against translations and rotations whereas, on the symmetric face, translations along x-direction and z-direction (see Fig. 4.5 for coordinate system) are zero. Following pictures depicts the restraint (Fig. 4.5) and force (Fig. 4.6) boundary conditions on the doubly curved die.

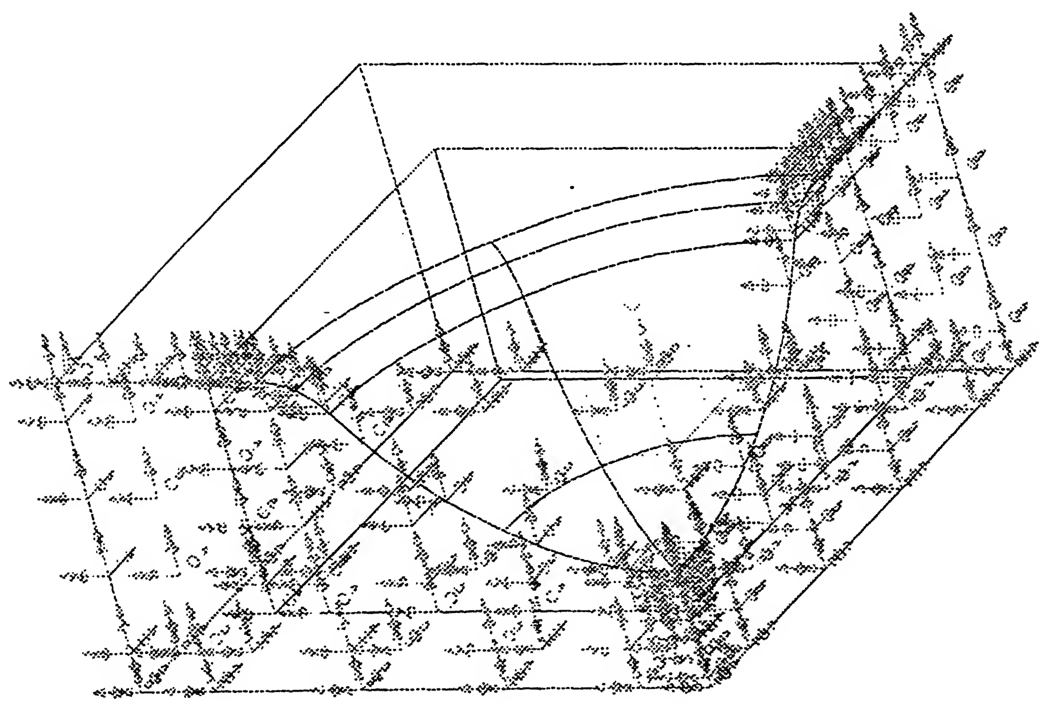


Fig. 4.5 Restraints on bottom and symmetric faces

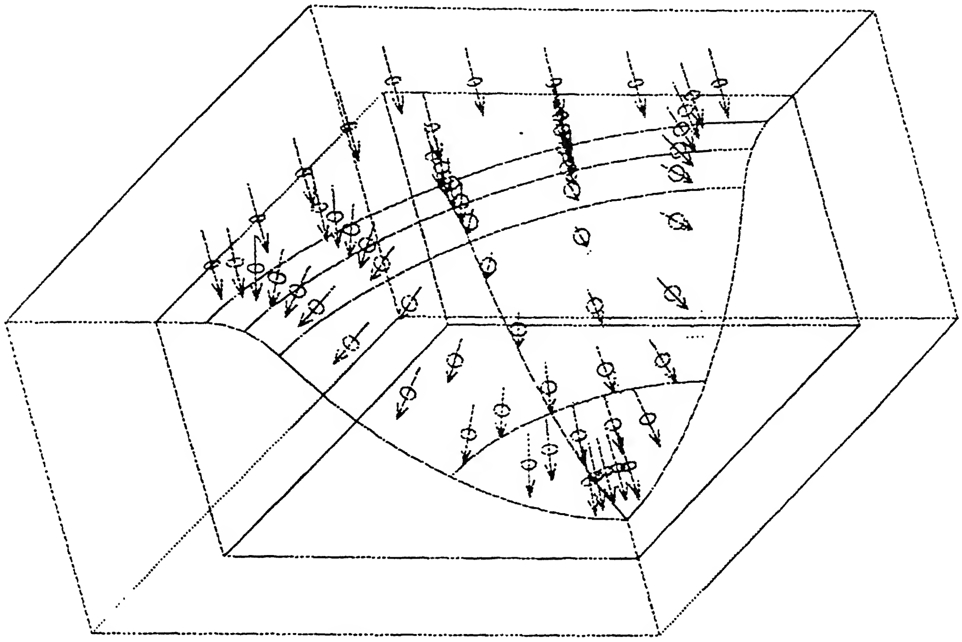


Fig. 4.6 Pressure on the surface – Force modeling

4.6.3 Mesh Generation

A solid tetrahedron mesh of parabolic order with 24,647 elements is generated on this volume. Of course this number is arrived after many trials conducted by the author using I-DEAS Simulation tool. Only at this the convergence is reached for this problem. The mesh is shown in Fig. 4.7

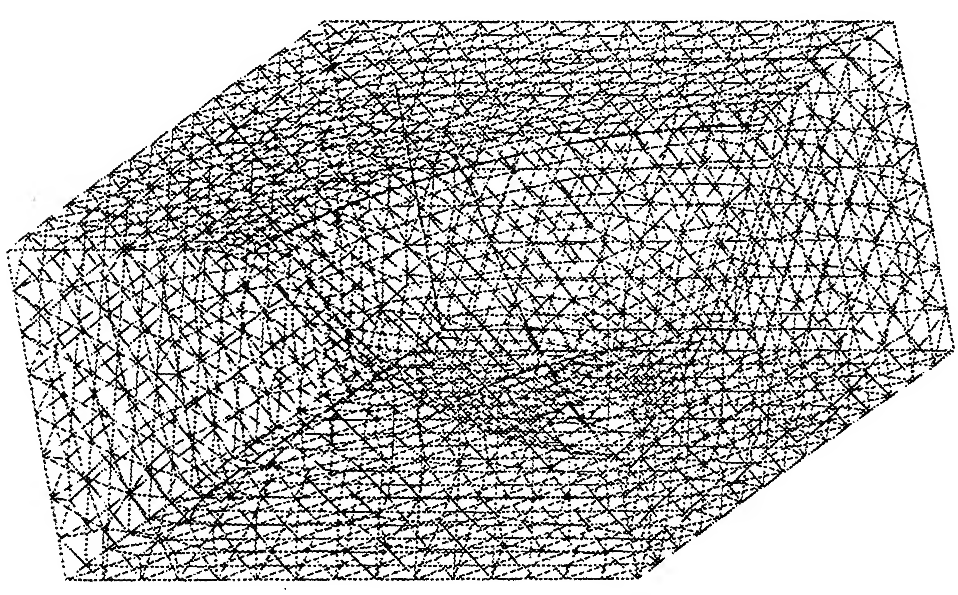


Fig. 4.7 FE mesh for the die shown in Fig. 4.6

4.6.4 Theory of Failure

The theory of failure applicable for brittle material can be used. In this context "*maximum principal stress theory*" would be the right candidate of choice.

Hence in the present work the "*maximum principal stress theory*" is used as theory of failure.

4.6.5 Model Solution

In the first case Doubly curvature die is chosen. A uniform distributed force of magnitude 1550 N was applied for making FRP composites parts using fiber cloth and hardener (Epoxy). The finite element model was solved with the *sparse matrix solver.* The results are as given below.

- First Principal Stress:
  - Maximum 1.27 X E+05 Pa
  - Minimum -2.47 X E+05 Pa
- Displacement 9.37 E-04 mm
- Computation Time 747 sec

The stress contours are shown in Fig. 4.8

The same problem is solved with *iterative solver.* The results obtained are given below.

- First Principal Stress:
  - Maximum 1.27 X E+05 Pa
  - Minimum -2.47 X E+05 Pa
- Displacement 9.37E-03 mm
- Computation Time 160 sec

It is worth to notice that there is no change in results. But there is a dramatic reduction in computation time. To understand this, a small background of solution algorithm is necessary.

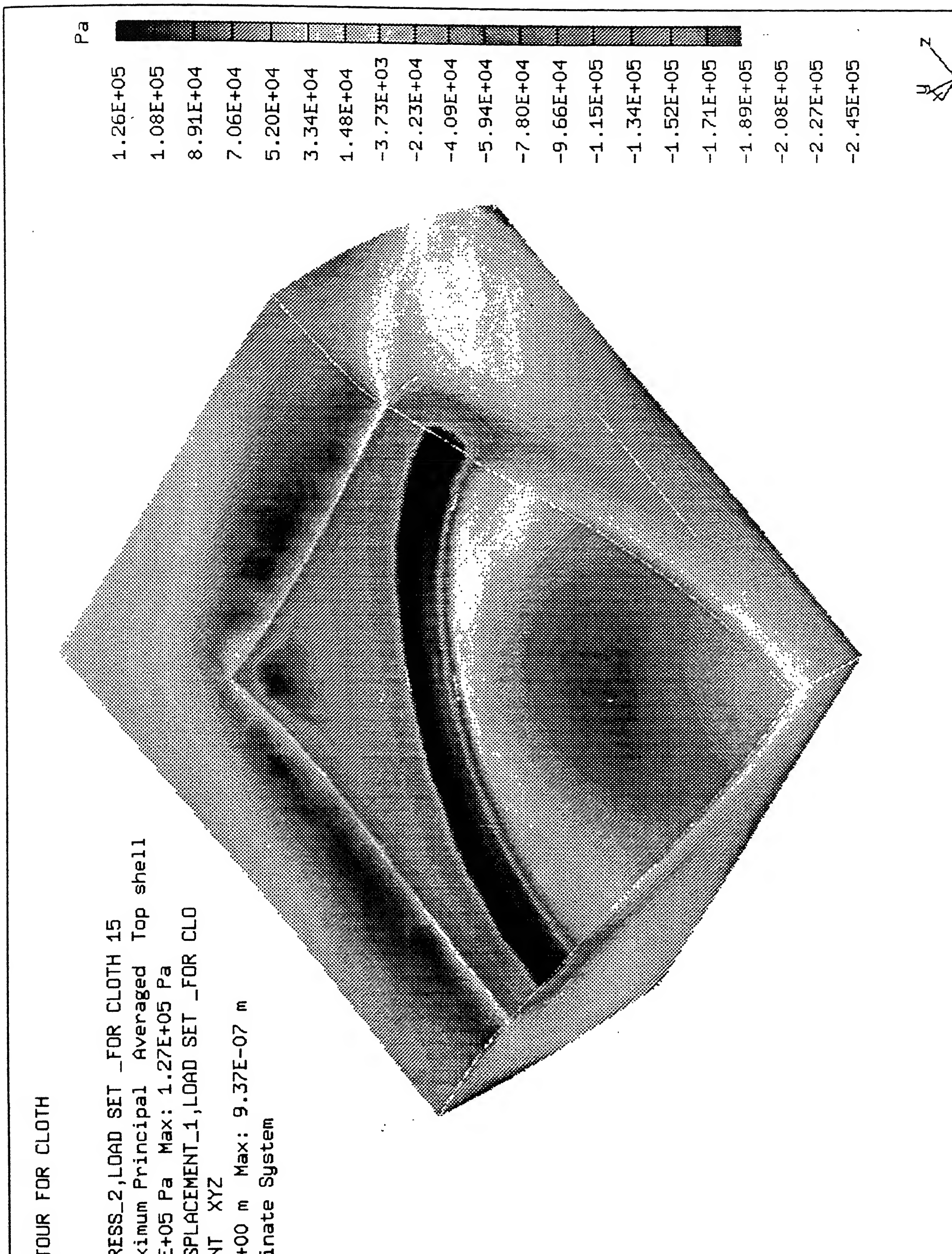


Fig 4.8: Stress Contour Plot for Fiber Cloth Processing on Doubly Curved Die at 1550 N

The resultant equation to be solved, for any finite element problem (see section 4.3) will look like

$$\mathbf{Kx} = \mathbf{b}$$

Let the residual $\mathbf{r} = \mathbf{b} - \mathbf{Kx0}$

Where, x0 is the current solution. The *iterative solver* takes a parameter called convergence tolerance. The solver will stop the iteration if the magnitude of this residual r becomes lesser than the tolerance specified. Whereas, the sparse matrix solver will try for an exact solution, which will naturally take more time. It has been found [20], for solid elements, iterative method converges faster. More details can be found elsewhere [20].

The same problem was run with loading same loading but for making parts using unidirectional prepreg at 110°C and loading of 3520 N. The results obtained are given below.

- First Principal Stress:
  - Maximum 2.85 X E+05 Pa
  - Minimum -5.56 X E+05 Pa
- Displacement 2.11E-03 mm
- Computation Time 160 sec

4.6.6 Loading Calculations

1. Loads on Singly Curved Die for Fiber Cloth

Optimum Pressure on die	= 3 kg/cm^2 (by Experiment)
Piston Area of Press Machine	= 50.2 cm^2
Weight of Punch	= 8.5 kg
Total Load on Die	= (3 X 50.2) + 8.5 kgf
	=159.1 kgf = 1570 N (approx.)

2. Load on Singly Curved Die for Prepreg

Optimum Pressure	= 7 kgf/cm^2. (by Experiment)
Piston Area of the Press Machine	= 50.2 cm^2.
Weight of the Punch	= 8.5 kgf.
Total Load on Die	= (7 X 50.2) + 8.5 kgf.
	= 359.9 kgf = 3535 N (approx.)

3. Load on Doubly Curved Die for Cloth

Optimum pressure	= 3 kgf/cm^2. (by Experiment)
Piston Area of the Press Machine	= 50.2 cm^2
Weight of the Punch	= 7 kgf.
Total Load on Die	= (3 X 50.2) + 7 kgf.
	= 157.6 kgf. = 1550 N (approx.)

4. Load on Doubly Curved Die for Prepreg

Optimum pressure	= 7 kgf/cm^2. (by Experiment)
Piston Area of the Press Machine	= 50.2 cm^2
Weight of the Punch	= 7 kgf.
Total Load on Die	= (7 X 50.2) + 7 kgf.
	= 358.4 kgf. = 3520 N (approx.)

5. Load on Cylindrical Cup Die for Aluminium & Steel Sheet

Cup Diameter (d)	= 100 mm.	Height (h)	= 25 mm.
Sheet Thickness (t)	= 1 mm.	Die radius	= 4t = 4 mm
Corner Radius on Punch (r)	= 6 mm.		

Blank Size (D) $= \sqrt{d^2 + 4\,d\,h} = \sqrt{100^2 + 4 \times 100 \times 25}$

$= 141.421$ mm.

$= 148$ mm. (for trimming allowance)

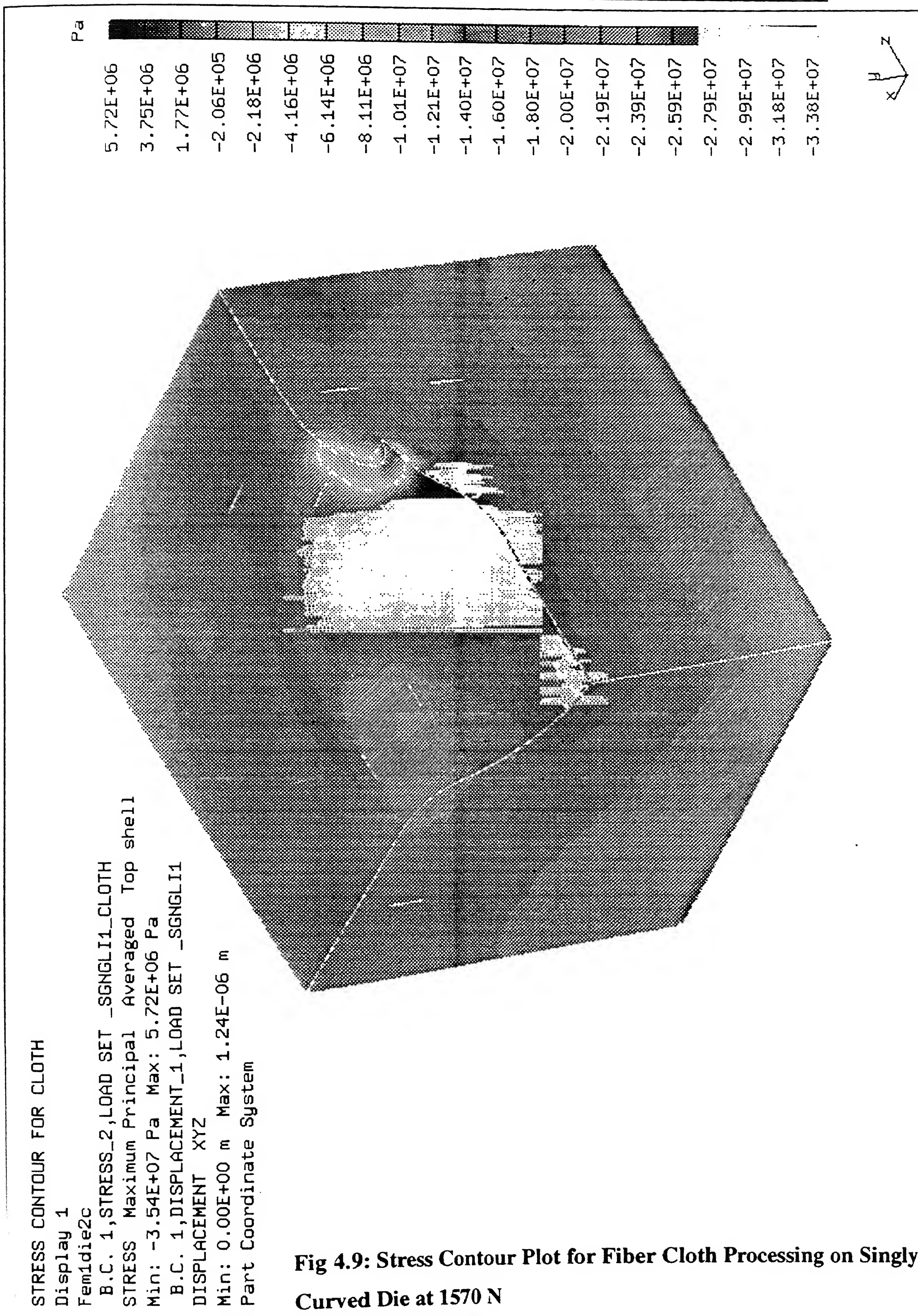


Fig 4.9: Stress Contour Plot for Fiber Cloth Processing on Singly Curved Die at 1570 N

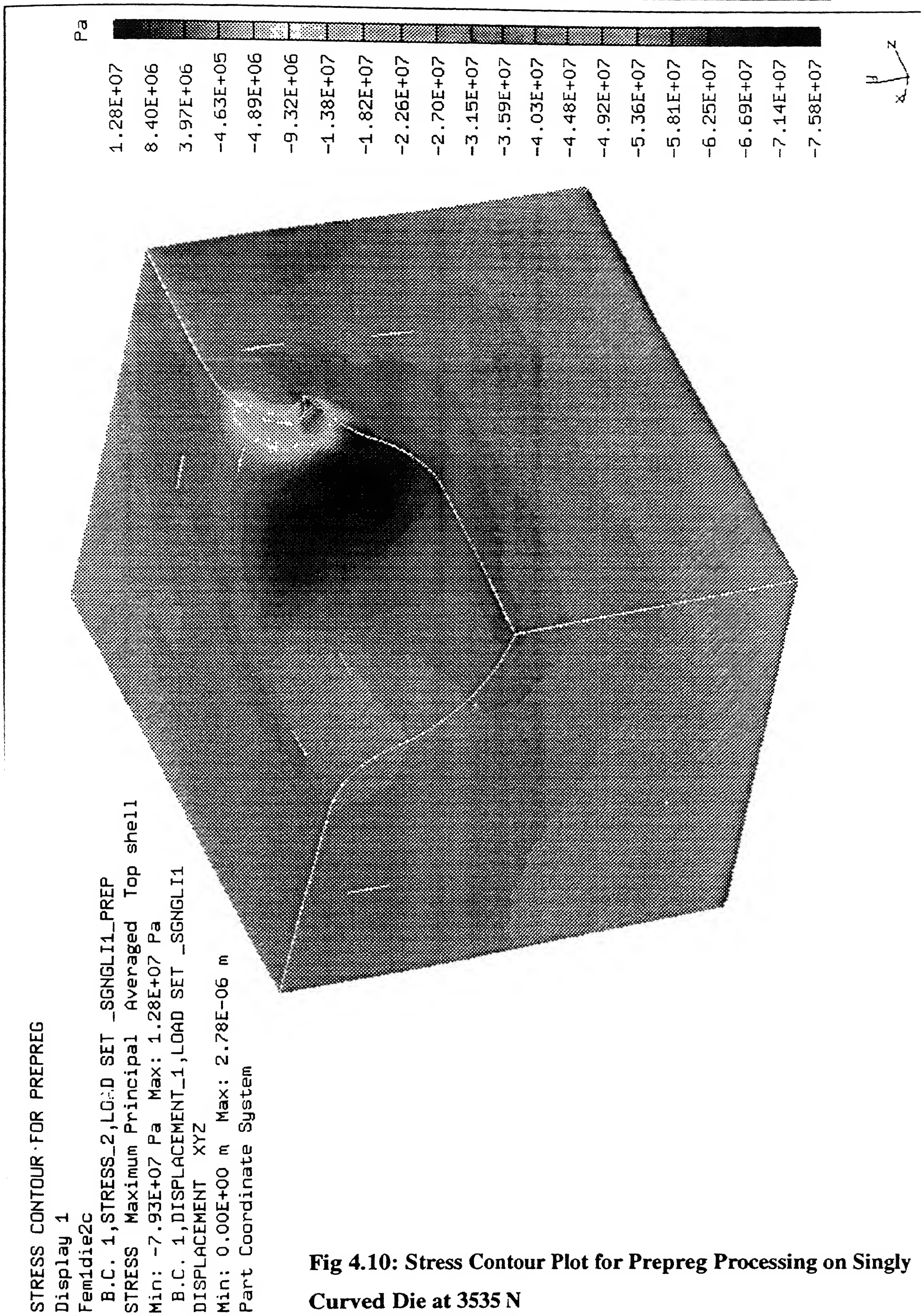


Fig 4.10: Stress Contour Plot for Prepreg Processing on Singly Curved Die at 3535 N

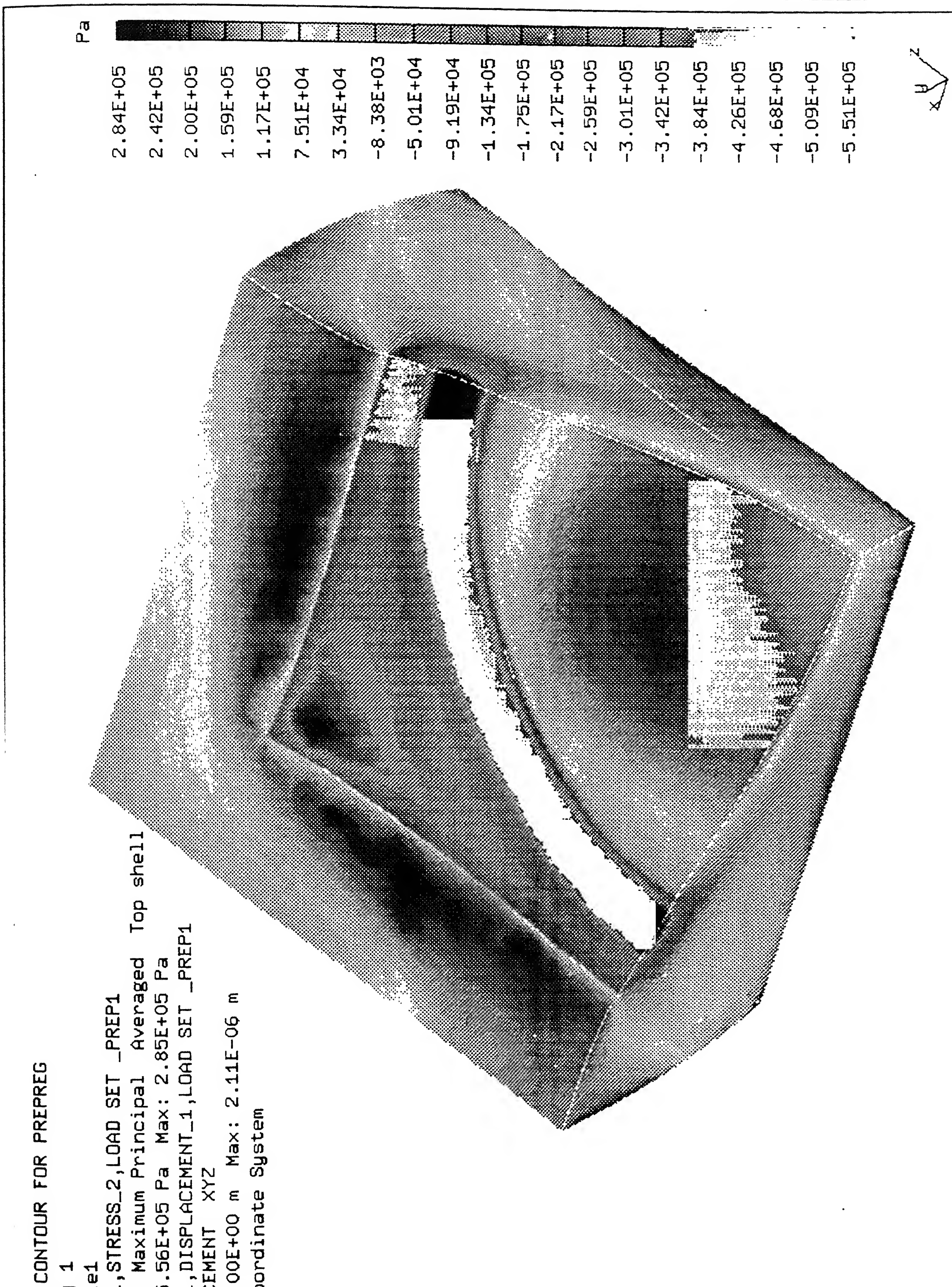


Fig. 4.11: Stress Contour Plot for Prepreg Processing on Doubly Curved Die at 3520 N

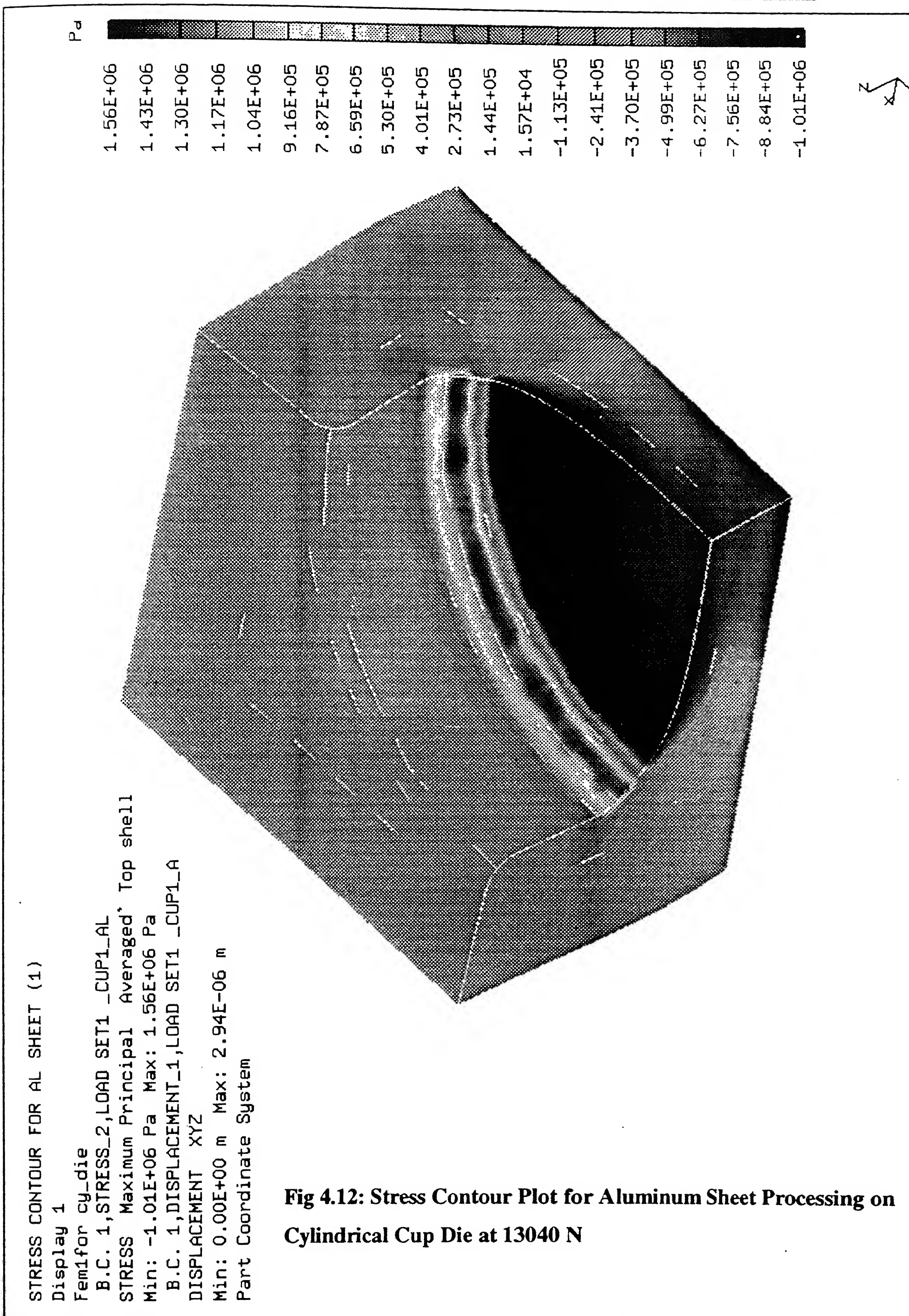


Fig 4.12: Stress Contour Plot for Aluminum Sheet Processing on Cylindrical Cup Die at 13040 N

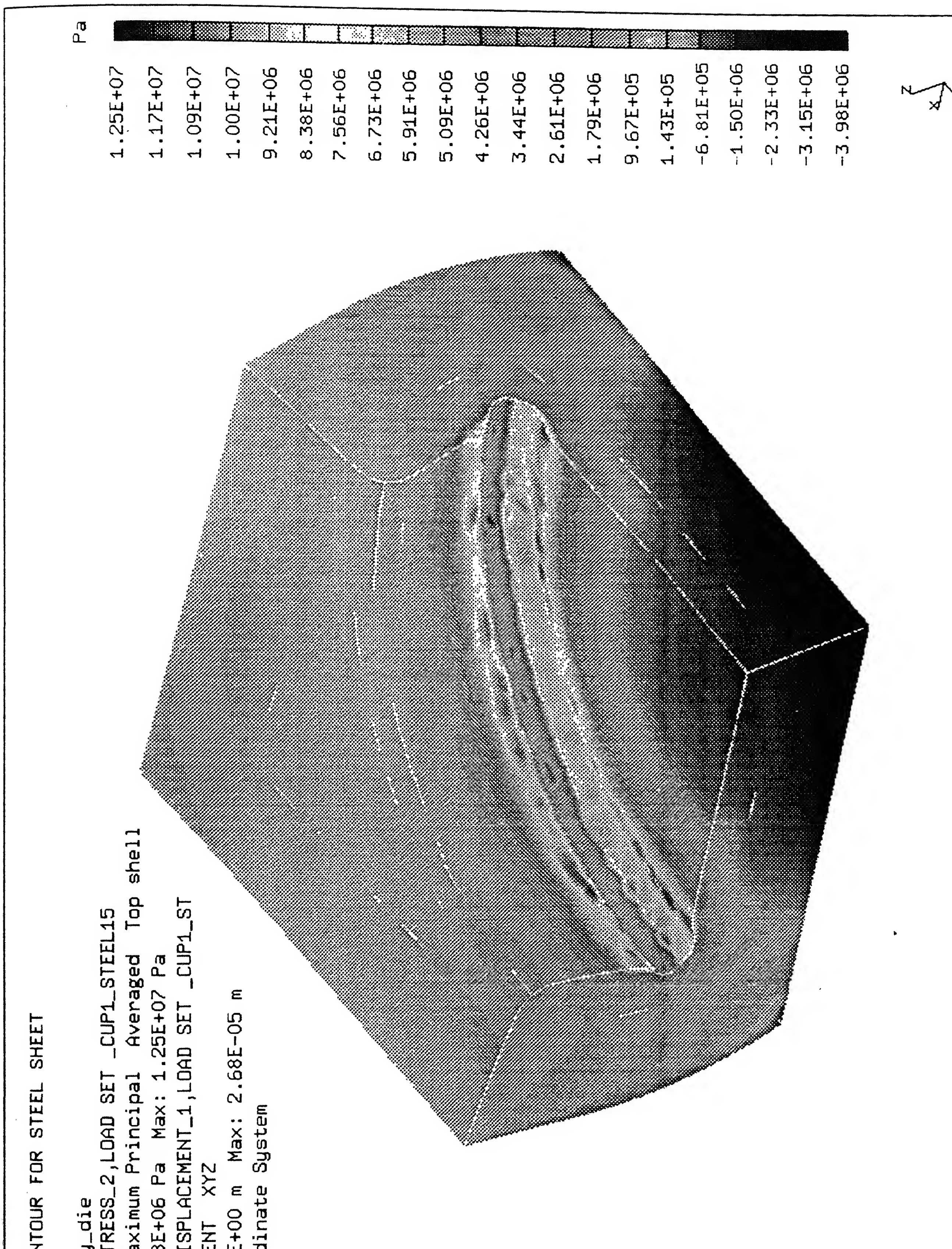


Fig 4.13: Stress Contour Plot for Steel Sheet Processing on Cylindric Cup Die at 78230 N

Drawing Force (P) = Π d t S (D/d - C)

Where,

S = Yield Stress of material = 50 MPa

C = Constant to cover friction and bending (0.6 to 07)

$\therefore$ P = Π X 100 X 1 X 50 X(148/100 – 0.65) = 13037.61 N

= 13040 N (Approx.)

For Steel,

In place of S = 50 MPa

S = 300 MPa

$\therefore$ P = 78225.657 N.= 78230 N (approx.)

4.7 Results And Discussions

To get the results, same exercise was repeated for all cases listed in Section 4.3. The results are tabulated below.

S. No.	Type of Die	Material / Processed	Load (N)	Max^m. Stress (MPa)	Min^m. Stress (MPa)	Max^m. Displacement (mm.)
1.	Singly Curved	Fiber Cloth	1570	5.72×10^{6}	-3.54×10^{07}	1.24×10^{-06}
2.	Singly Curved	Prepreg	3520	1.28×10^{7}	-7.93×10^{07}	2.78×10^{-03}
3.	Doubly Curved	Fiber Cloth	1550	1.27×10^{5}	-2.47×10^{5}	9.37×10^{-04}
4.	Doubly Curved	Prepreg	3535	2.85×10^{5}	-5.56×10^{5}	2.11×10^{-03}
5.	Cylindrical	Aluminium Sheet	78230	1.56×10^{6}	-1.01×10^{6}	2.94×10^{3}
6.	Cylindrical	Steel Sheet	13040	2.08×10^{6}	-6.63×10^{5}	4.46×10^{-03}

Table 4.2

From the above results, it is clear that the maximum and minimum stress developed in these dies for different types of composites processing are too much below the failure stress of the material. The maximum displacement due to the stress is also very less. There dies are also found suitable for composite processing experimentally and varieties of FRP composites have been successfully made on these dies.

The stress analysis of a simple die for shallow drawing of a cylindrical cup has been done for thin sheet of aluminium and steel sheet has been done. It has been found that compare to composites processing here stresses are quite high for these two cases, but it is also below the limiting stress of the die material. So, these sheets can also be processed successfully on this die.

Chapter 5
CONCLUSIONS

5.1 Case Studies

In the present work, an attempt has been made to develop different processes of making press-tool dies for various applications like FRP composite processing and sheet metal forming processes by the integration of different RP processes and Rapid Tooling systems. Also, stress analysis of some simple curvature dies has been done using FEM package I-DEAS to find the suitability of these dies in various applications. In contrast to the conventional die making processes like CNC milling, cutting etc. here, dies were made from casting process. So, it requires pattern. Pattern making in a conventional methodology is a time consuming process and hence rapid prototyping was chosen as a pattern making methodology. In rapid tooling system for making dies, RP pattern was used.

Three simple shapes of dies were chosen for present work, namely singly curvature die, doubly curvature die and shallow cup drawing die. The whole work encompassing RP, MCP Low Melting Alloy System and FRP composite processing using these dies posed a number of challenges, which were overcome successfully.

5.2 TECHNICAL SUMMARY

RP technology has proven to be a boon for designers. Designers can have the pattern ready in a very short time, which can be used for making the tool like press-tool dies, injection molding dies etc. The pattern made from the fused deposition modelling system are porous and this makes the low melting alloy or plaster of paris, used in casting process to enter the pores in the pattern. The removal of pattern from the casted die becomes difficult due to this problem. In case of pattern with deep holes

removal of pattern from the die is much more difficult. Sufficient care has to be taken in pattern preparation when using the FDM component to ensure that the MCP 137 alloy or plaster of paris does not enter in to the pores. As compared to the FDM process the SGC process gives solid components. They do not have the problem of porosity. Hence for pattern, with the deep holes, SGC is to be preferred for making the master pattern. With the new developments in the field of metal spraying techniques like MCP-TAFA metal spray systems, in the FDM components these shortcomings can be overcome upto some extent.

Press-tool dies have been successfully made for a number of components like singly curved die, doubly curved die, cylindrical shape die and a complex curvature die for car body etc. The Rapid tooling is getting overwhelming response from mold making industries. It has become one of the hot topics for research also. Every RP manufacturer is trying to inter-link with RT process.

In the present work, dies were prepared using the system installed at CAD-P Lab, ME department, IIT Kanpur. Parts by Fusion Deposition Modeling and Solid Ground Curing RP system were used as master pattern for preparing dies for FRP composites and sheet metal processing. Dies were made with different methods. This has given a qualitative evaluation. To be more scientific, a quantitative evaluation is attempted. FEM was used as the tool for evaluation. FEA was done for different applications. Reasonable results have been achieved.

5.3 SCOPE FOR FUTURE WORK

- A better release agent should be found out for Prepreg processing.
- In the present work, FDM and SGC patterns were used. As the MCP 137 alloy copies the surface texture, so, FDM process may not the best RP process to use with. And the problem with SGC process was that it becomes flexible at 80°C so, it is very difficult to make the die using SGC pattern. One remedy is to adopt the finishing processes prescribed by Stratasys Inc. [21] for FDM pattern. Attempts should be made to use other RP processes so as to get a better surface texture.

- The MCP Low Melting alloy is not only limited to make the Press tool die but it can be directly poured in to Silicone mold and good surface finished part can be obtained, which can be used in other process like injection molding for making the core.
- Accurate modeling of the press-tool die for sheet metal component should be done to get still better results.
- Sheet metal processing of some complicated parts should be tried out on some press machine using the die made of MCP-137 alloy.
- The life cycle of the die should be found out for the various applications.

[1] Kai C.C. & Fai L.K., "Rapid Prototyping – Principal and Applications", Wiley *Eastern New York*, 1996.

[2] "Rapid prototyping and tooling, New paradigms in Design and Manufacturing", Rapid Prototype cell, IIT Mumbai 1998.

[3] Jacob P. F., "Rapid prototyping & manufacturing, Fundamentals of stereolithography" First edition, 1992.

[4] FDM system Documentation by Stratasys Inc., May 1996.

[5] Solider System Documentation by Cubital Inc., Israel, Jan 1998.

[6] Peter Hilton, "Making the leap to rapid tool making", *Mechanical Engineering*, July 1995, pp 75-77.

[7] Roger Maddox & John Knesek, "A glimpse at rapid prototyping technologies", *Aerospace America*, June 1993, pp 28-32.

[8] Dhande S. G., "Rapid Tooling Lecture Notes", *CAD Project, I.I.T. Kanpur*, 1998.

[9] Phill Dickens, "Rapid Tooling: A Review of the Alternatives", *Rapid News*, Volume 4, Number 5, pp 54-60.

[10] Frank Breitinger& Munich, "Rapid Tooling for Simultaneous Product and Process Development (Part I)", *Rapid News*, Volume 5,Number 5, pp 44-48.

[11] Frank Breitinger& Munich, "Rapid Tooling for Simultaneous Product and Process Development (Part II)", *Rapid News*, Volume 5,Number 6, pp 52-57.

[12] MCP Low Melting Alloy System Documentation by HEK GmbH, Germany., Jan 1998.

[13] Anil Kumar M., "Rapid Prototyping, Rapid Tooling and Digital Photoelasticity: An Integrated Approach", M.Tech thesis, IIT Kanpur, 1998.

[14] Sridharan, V., "Effect of Metal Spray Coating on Epoxy Tooling", M. Tech thesis, IIT Kanpur, 1998.

[15] Rao P.N., "Manufacturing Technology", *Tata McGraw-Hill*, 1987.

[16] Donald F. Fary & Edward A. Reed, "Techniques of Pressworking Sheet Metal: An Engineering Approach to Die Design", *Prentice-Hall, Inc.*, 1974.

[17] Paquin J.R. & Crowley R.E, "Die Design Fundamentals", *Industrial Press Inc.*, 1987.

[18] Reddy J.N., "An introduction to finite element analysis", *McGraw Hill*, 1993.

[19] TAFA "Arc spray application data", by TAFA Inc., Jan. 1998.

[20] I-DEAS "Smartview-Finite Element Simulation Guide", Structural Dynamics Research Corporation, Milford, Ohio, 1997.

[21] FDM System Documentation by Stratasys Inc., May 1996.

[22] Solider System Documentation by Cubital Inc., Israel, Jan 1998.

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